Marching across Anatolia

Medieval Logistics and Modeling the Mantzikert Campaign

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In 2007 the organizers of a major demonstration in London reported crowds of 60,000, whereas the police reported just 10,000. In June of 2011, a huge crowd gathered in Hong Kong for a vigil to commemorate the twenty-second anniversary of the Tiananmen Square massacre in Beijing. In some reported versions of the event, there were 77,000 people present; in others, the numbers doubled to 150,000. Official estimates were, predictably, lower; and it is clear, as recent debates about the size of political rallies in the United States underscore, that such figures are both very difficult to arrive at and regularly subject to manipulation by those supporting the event and those opposed to it, or by the organizers and, say, security or police forces. Recent scientific research has generated a number of (to the outsider) fairly complex mathematical formulae and methodologies for addressing such issues, but the fact that estimating the size of large crowds is fraught with problems is generally recognized.[1] It is, of course, not a new problem. Numbers in ancient and medieval texts are notoriously problematic—sometimes entirely plausible and seemingly trustworthy, according to our modern ideas of what is possible or not under certain sorts of conditions; sometimes entirely incredible, yet at the same time not always to be cast aside or ignored, perhaps having a symbolic or indicative value even if not providing an exact arithmetic count. Fulcher of Chartres, an eyewitness, reports that the forces of the First Crusade at Nicaea in 1097 numbered 100,000. He reports further that 5 million noncombatants were also present! By contrast, another eyewitness, Raymond of Aguilers, reports that by the time the army reached Jerusalem it had been reduced to just 12,000.[2] Historians generally credit the latter figure with a high degree of plausibility and view the former as having a purely symbolic value, suggesting simply "very large." Given that medieval people, in the western Eurasian world at least, rarely had to confront large numbers of people gathered together, it is reasonable to suppose

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1 See esp. R. Watson and P. Yip, "How Many Were There When It Mattered?" *Significance* 8 (2011): 104–7; L. E. Aik and Z. Zainuddin, "Curve Analysis for Real-Time Crowd Estimation System," *European Journal of Scientific Research* 38.3 (2009): 441–53; A. N. Marana, L. da F. Costa, R. A. Lotufo, and S. A. Velastin, "Estimating Crowd Density with Minkoski Fractal Dimension," *Proceedings of the International Conference on Acoustics, Speech, Signal Processing* 6 (1999): 3521–24; and S. A. Velastin, J. H. Yin, A. C. Davies, M. A. Vicencio-Silva, R. E. Allsop, and A. Penn, "Analysis of Crowd Movements and Densities in Built-Up Environments Using Image Processing," *Image Processing for Transport Applications, IEE Colloquium* 8 (1993): 1–6.

2 See J. France, "Size," in *The Oxford Encyclopedia of Medieval Warfare and Military Technology*, ed. C. J. Rogers, 3 vols. (Oxford, 2010), 1:65–67.

that when substantial armies were seen the observer had no way of calculating the numbers with any hope of accuracy, although it is possible that military men themselves, or those familiar with such concentrations, could arrive at more reasonable estimates.

Problems with numbers are just one facet of the study of logistics, however. Medieval historians have only rarely examined the logistical issues associated with warfare (with some exceptions in respect of the study of the Crusades), although historians of the ancient and early modern worlds have devoted considerable effort to the issues they raise.[3] But in looking at questions of military logistics we inevitably also need to deal with much wider issues of demography, settlement patterns, land use and resource allocation, distribution, and consumption that affect medieval societies and economies more broadly; moreover, we need to highlight the limitations we face when relying on traditional historical and archaeological approaches alone in attempting to examine such questions. And there is a quantitative gap in our knowledge as well, since the amount of resources available or under discussion in a particular historical context, along with the relationship between people, resources, and levels of productivity, is generally unknown or arrived at only with great difficulty.[4] This means that a number of key issues remain unexplored: the question of population size and demography, for example, in the medieval Eastern Roman Empire in the seventh or eighth or twelfth century;[5] the nature of the relationship between agrarian production, settlements, and population size; the size of the armies mentioned in the sources; and the plausibility of the figures those sources sometimes give. Hypotheses based on more or less credible criteria can certainly be constructed, invoking probable capacities and enabling us to build into our model as much archaeological, ecological, and other relevant evidence as possible; and we can weigh our documentary information against this model to establish a more-or-less plausible context and thus set limits to our interpretation. But the margin of discrepancy is still so large, and the variables and uncertainties still so many, that such an approach merely promotes circular discussion rather than offering an empirically or objectively determined solution.

Argument over the same sparse references in a few medieval texts gets us no further in our efforts to understand such matters, and the conclusions drawn by even the most competent and wide-ranging scholars generally remain almost entirely subjective and unfalsifiable, because the information needed to test such hypotheses and such interpretations is lacking. In approaching issues such as the size of armies,

3 See, for example, P. Erdkamp, *Hunger and the Sword: Warfare and Food Supply in Roman Republican Wars (264–30 B.C.)* (Amsterdam, 1998); the essays in *The Roman Army and the Economy*, ed. P. Erdkamp (Amsterdam, 2002); R. Duncan-Jones, *Structure and Scale in the Roman Economy* (Cambridge, 1990); and the general discussion of L. W. Marvin, "Logistics and Transportation," in Rogers, *The Oxford Encyclopedia of Medieval Warfare and Military Technology*, 2:513–17.

4 Preliminary efforts have been made, based primarily on written documents, for the armies of Alexander the Great, the Roman and Byzantine armies, and the Ottoman army, and some work has been done on western medieval armies and the Crusader forces: D. W. Engels, *Alexander the Great and the Logistics of the Macedonian Army* (Berkeley, 1978); P. Roth, *The Logistics of the Roman Army at War (264 B.C.–A.D. 235)* (Leiden, 1999); and R. Murphey, *Ottoman Warfare, 1500–1700* (London, 1999), with the literature cited in the preceding note. For Byzantium, see the essays in *General Issues in the Study of Medieval Logistics: Sources, Problems and Methodologies*, ed. J. F. Haldon (Leiden, 2005), particularly J. F. Haldon, "Why Model Logistical Systems?," 1–35; and idem, "Roads and Communications in the Byzantine Empire: Wagons, Horses, Supplies," in *The Logistics of the Crusades*, ed. J. Pryor (Sydney, 2005), 131–58, with previous literature. Sections in many other works likewise contain useful discussions of logistical issues and reviews or discussions of the older literature, such as H. Delbrück, *History of the Art of War*, trans. W. J. Renfroe, Jr., 4 vols. (Lincoln, 1990); cf. J. France, *Victory in the East: A Military History of the First Crusade* (Cambridge, 1994), and idem, *Western Warfare in the Age of the Crusades, 1000–1300* (London, 1999), which takes into account earlier literature on western and Crusader army logistics. There is, in addition, a huge bibliography for the more recent preindustrial or early industrial periods (for example, the logistics of the Thirty Years' War or the campaigns of Napoleon or Wellington in the period 1798–1815), which cannot be reproduced here. For some notion of this coverage, see M. Van Crefeld, *Supplying War: Logistics from Wallenstein to Patton* (Cambridge, 1977); and J. Keenan, "Logistics and Supply," in *A History of Warfare* (London, 1993), 301–15.

5 See below; and for Byzantium, see A. Laiou, "The Human Resources," in *The Economic History of Byzantium from the Seventh through the Fifteenth Century*, ed. A. Laiou et al., 3 vols., DOS 39 (Washington, D.C., 2002), 1:47–55; for some general observations, F. Braudel, *The Mediterranean and the Mediterranean World in the Age of Philip II*, trans. S. Reynolds, 2 vols. (London, 1973), 1:396–411; J. C. Russell, *Late Ancient and Medieval Population* (1958; reprint, Philadelphia, 1963); and with a summary of more recent evidence, M. McCormick, *Origins of the European Economy: Communications and Commerce, A.D. 300–900* (Cambridge, 2001), 31–36. See also G. D. R. Sanders, "Reassessing Ancient Populations," *BSA* 79 (1984): 251–62.

researchers must take into account the environment that had to support them; further, if information can be obtained about the capacity of a given area to support a resident population at any particular moment, then something might also be said about the capacity of that area to support additional numbers of people—a transient population of soldiers and their animals, for example—and how long such support might be sustained. Such an inquiry has to be a multidisciplinary undertaking—the specialist information generated by paleoclimatologists, palynologists, and geomorphologists relating to ancient landscapes and climate alone offers a vast amount of data that can only with great difficulty can be adequately explored and understood by the historian, and it is simply not possible for an individual to master all the necessary technical expertise in all the fields and disciplines relevant to such an enterprise. What is required is a combination of skills and expertise in complementary fields that, when more closely integrated in the framework of a single scientific inquiry, may be able to offer some solutions for, or at least some guidance about, the questions asked above.

In order to address some of these issues, a project that combined the resources of historians, archaeologists, and computer scientists was launched at the University of Birmingham (UK) and at Princeton University. The project has been designed to offer a fundamental reanalysis of an exemplary campaign for which a reasonable amount of historical evidence is available: that which led to the Battle of Mantzikert in the year 1071.[6] In addition, the project is intended to illustrate the use of simulation techniques to model the movement and sustainability of historic armies, with multiple simulations of military forces moving within a digital environmental database. Alongside primary and secondary source material, the data are employed to interpret events related to the battle and to assess interpretations of the historical sources. Since such simulation methodologies have a wide applicability, permitting the reuse of models and processes in comparable regional or period studies, the project is relevant to a much broader range of questions than those concerned with military campaigns alone and, it is hoped, will be of value to the study of premodern economic history more widely. The project is configured as one element in the wider Medieval Logistics Project, established originally at the University of Birmingham by John Haldon in 1999 and now managed jointly by faculty at Birmingham and at Princeton.[7] In essence, the major goals of the project are

1. To establish a novel, rigorous computational framework for the analysis of historical military logistical data (pertaining to movement, communications, and settlement, and to production, allocation, and consumption of resources) for the early medieval periods in Europe and the Near East.
2. To create a reusable Grid-enabled simulation[8] and data analysis infrastructure that supports the framework outlined above.
3. To use a Grid-modeling framework to improve our understanding of the central role of warfare and conflict in the medieval periods; to use the results of multiple simulations of the Mantzikert campaign to critique previous research.
4. To demonstrate, using the Mantzikert campaign, the opportunities offered to the historical community by large-scale distributed simulation technologies and to present fundamentally new insights into long-standing historical questions.

In what follows we will outline the historical evidence for the campaign of 1071, point out some of the major questions that remain unresolved or

6 We will retain the traditional Anglicized version of the name, although in fact it should be transliterated Mantzikiert, the usual form found in the Greek sources of the period: see B. Coulie, "Manzikiert ou Mantzikiert? Note sur le *De Administrando Imperio*," *Byzantion* 56 (1986): 342–48 (we are grateful to Johannes Koder for this reference). The main sources for the events of the campaign are the accounts of the eyewitness Michael Attaleiates, who was present as a senior but nonmilitary officer in the emperor's entourage, *Michaelis Attaliotae Historia*, ed. I. Bekker, CSHB [47] (Bonn, 1853), 147–67, and of Nikephoros Bryennios, the grandson of the general (also named Nikephoros Bryennios) who was commander of the left wing at Mantzikert, *Hyle historias*, ed. P. Gautier, *Nicéphore Bryennios, Histoire*, CFHB 9 (Brussels, 1975), 111–19. See the literature cited in n. 11 below.

7 See the papers from the first Logistics Workshop: Haldon, *General Issues in the Study of Medieval Logistics*.

8 We will define and clarify the technical terms more precisely below, but a Grid-enabled model is simply one that requires the computing power of a number of separate machines working together, linked through a single interface.

unanswerable by established methods of historical inquiry, and then set out the details of the simulation. Those unfamiliar with computer science may find the second part somewhat technical in many respects, but we hope they will bear with the argument in order to see how such a project will contribute to a better understanding of such historical events as well as of a range of broader problems in the economic history of premodern societies. The aim is to suggest not that historians should become computing experts but that historians and computer scientists can work together fruitfully to achieve goals within their own disciplines.

The basic outline of the campaign is relatively well-established. In the winter of 1070–71, the emperor Romanos IV prepared a major expedition, directed against the Seljuk garrisons that had been placed in the Byzantine border fortresses at Khliat and Mantzikert in the east. His intention was to reestablish the frontier defenses as fully as he could. We can map the route taken across Asia Minor fairly accurately, and figure 1 shows a version of that route, reconstructed on the basis of information collated from the relevant *Tabula Imperii Byzantini* maps of the areas in question, from the contemporary and near-contemporary sources, from the Ottoman military road system, and from modern satellite mapping sources.[9]

By late June the imperial forces had reached Erzurum (Theodosiopolis), where a decision had to be made as to which direction the army should proceed and exactly what strategy the emperor should implement. There appears to have been some dissension. Some of the generals suggested he move on, try to outflank the sultan and take the war into Seljuk territory, and bring him to battle. Others, including the generals Joseph Tarchaneiotes and Nikephoros Bryennios, argued that the emperor should instead pause, fortify the surrounding towns and strengthen their garrisons, lay waste the countryside to deprive the approaching Turks of necessary supplies, and await events. The latter course of action seemed inappropriate, particularly since the army was clearly in danger of running out of supplies if it waited in one place for too long, and so the order was given to move on.

It is difficult to estimate the forces at the emperor's disposal at this point, but he had by no means denuded the empire of troops for this campaign. A detachment of Varangians was certainly left in the imperial palace; a detachment of Frankish heavy cavalry under their leader Krispos had been left at Abydos; and since both the Normans and the Hungarians were a threat at different points in the Balkans, the garrisons in these regions would surely not have been reduced. It may have been to these areas that the unruly German contingent was posted. The field troops in Syria, and in particular those under the *doux* or military governor of Antioch, remained substantial, as later events demonstrate, even though some reinforcements to the emperor's field army had been sent from Syria. The contemporary sources also make it clear that after the battle, considerable numbers of troops were still in their garrisons and posts throughout Anatolia.

Of the units that accompanied the emperor, some are mentioned in the sources by name: the Franks under Roussel de Bailleul, who may have numbered 200–300 or more; the five *tagmata* of the West; a number of detachments of Oğuz (Turk) mercenaries, whose exact number is unknown; troops from Bulgaria; and indigenous eastern thematic tagmata from Cappadocia, and probably also from Koloneia, Charsianon, Anatolikon (units from Pisidia and Lykaonia are mentioned in earlier campaigns for the 1050s), Chaldia (Trebizond), and Armeniakon. Units from Cilicia and Bithynia are also mentioned in one of the sources. Tagmata from the field armies of Syria were present as well, though it is not certain how many. In addition to these troops, there were also substantial numbers of Armenian infantry units. Where these were drawn from is not known: possibly from the regions around Sebasteia and Theodosiopolis, as well as from the Syrian forces. In addition, there was a substantial body of Pecheneg mercenaries and allies, as well as some units from the allied or vassal states in the Balkans. Of the palace regiments, the soldiers of several other units—the *Hetaireia,* the *Scholai,* and the *Stratelatai*—made up a reserve division, and detachments of Varangians were also present.

The total of the forces the emperor assembled can only be guessed at. The medieval Islamic sources reckon it at anything from 100,000 to 300,000, figures preposterous in view both of the demography of the

9 See K. Belke, "Verkehrsmittel und Reise- bzw. Transportgeschwindigkeit zu Lande im byzantinischen Reich," in *Handelsgüter und Verkehrswege: Aspekte der Warenversorgung im östlichen Mittelmeerraum (4. bis 15. Jahrhundert),* ed. E. Kislinger, J. Koder, and A. Külzer (Vienna, 2010), 45–58, and map on 58.

FIG. 1. Anatolia and a route to Mantzikert (copyright J. F. Haldon, V. L. Gaffney, G. Theodoropoulos, and P. Murgatroyd)

empire at the time and of the logistics involved. Much depends on how large the units were—some tagmata may have numbered a mere 200–300 men, for example; others may have been larger, perhaps up to 500 or more. The figures we arrive at can thus vary between a grand total of fewer than 20,000 and as many as 60,000. The former seems unreasonably low, given that in the 970s the empire could field some 30,000 in the Balkans on occasion (though that force is described as a very large army by Leo the Deacon),[10] and the latter seems far too large. Perhaps 30,000–40,000 or so would explain the emperor's apparent confidence and his willingness to divide his forces (see below), as well as the Turkish sultan's obvious worries about the size of the threat.

The emperor's plan seems to have been to take both Mantzikert and Khliat, which lay somewhat to the south on the western shore of Lake Van. But he was completely misinformed about the movements of Alp Arslan and his troops. The latter, in fact, had not returned to Iraq at all; rather, he had marched directly toward the Armenian border by way of Amida and Mosul, then on to Khoi just to the north of Lake Urmia. There his vizier had proceeded to Azerbaijan to raise more troops, while he himself, reported to have collected some 10,000 cavalry from his allies and vassals en route, had by that time assembled a substantial force—by some estimates, as many as 30,000 horsemen.

From Erzurum the emperor advanced eastward. According to the eyewitness Michael Attaleiates, the troops were ordered to collect enough provisions for two months—a very considerable amount, which necessarily entailed the use of large numbers of pack animals and carts, slowing the army down somewhat. Some of these provisions were required for the march to Mantzikert, which seems to have taken about five weeks, and some for the army once it reached the area, lest the supplies there were inadequate. A substantial body of the Pecheneg allied force, closely followed by the Frankish troops under Roussel, was ordered ahead to the region around Khliat—which Romanos clearly perceived as the more difficult of his two first objectives—with instructions to collect fodder and provisions on the way, to prevent enemy damage to the harvest, and, presumably, to secure it for the imperial advance. The emperor must have continued his march east along the same route, before turning south to cross

10 See Leo Diaconus, *Historia* 8.4.19–21, ed. C. B. Hase, CSHB [5] (Bonn, 1828), trans. A.-M. Talbot and D. Sullivan as *The History of Leo the Deacon* (Washington, D.C., 2005), 179.

the Araxes, and then east, either along the valley of the Murat Su or a little further south (which is the route the forces under Roussel will have followed) at Muş (Taron), toward Mantzikert itself.

Before reaching this first objective, he detached a further substantial force under Tarchaneiotes, with orders to assist Roussel in taking and garrisoning Khliat. According to Attaleiates, these were most of the better and more battle-hardened units, an elite that included the Varangians and some of the Armenian infantry from the field forces under the doux of Theodosiopolis. He also notes that the troops remaining with Romanos were now fewer than those he had sent off to Khliat. We may surmise that after these various detachments were dispersed, the forces remaining with the emperor at this point likely numbered only some 20,000 or so, and were therefore—contrary to Romanos's expectation and assumptions—barely, if at all, superior in numbers to the main Turkish host.

The decision to detach the troops under Roussel and then Tarchaneiotes, based on the false assumptions that the enemy would approach from the south or east of Khliat and was still some distance away, proved to be a major blunder. Unaware of the closeness of the Seljuk forces, which were then approaching both Khliat and Mantzikert from the east, the two Roman commanders were suddenly confronted by what seemed to be a substantial enemy force. What happened next has no explanation in the sources, for both forces appear simply to have turned about and moved with great haste away from the Seljuks, whom they seem neither to have reconnoitered nor to have reported to the emperor, a mere 50 kilometers or less to the north. But the two divisions simply marched off toward Melitene (Malatya) on the Euphrates, and took no further part in the campaign.

Whatever the reason for this absence, the emperor was now deprived of some of his best and most reliable units. Unaware of the events to the south, he proceeded to Mantzikert, which capitulated without a struggle, the garrison being released without punishment. Romanos set up his camp outside the fortress and on the banks of a small tributary of the Murat Su, which flowed down from the Süphan Dağı. The rest of the story is well-known, and we will leave it now to examine more closely the logistics of this campaign.[11]

Discussion of the physical context for such a campaign must begin with the landscape and, more particularly, the communications network. One result of a number of changes that occurred between the third and the sixth–seventh centuries seems to have been an increasing reliance on beasts of burden, rather than on wheeled vehicles drawn by draft animals, for the movement of goods and people.[12] The archaeological evidence is clear in this respect—many inclines in hilly country were addressed with shallow steps, an obstruction to some larger or heavier wheeled transport, while the surface area of metaled roads was reduced.[13] Major arterial Roman roads in the eastern provinces were generally wider than 6.5 meters,

11 It is not our intention here to analyze the campaign in detail; we wish merely to sketch some key aspects in order to illustrate the value of the agent modeling and simulation. For accounts of the Mantzikert campaign, see J.-C. Cheynet, "Mantzikert: un désastre militaire?," *Byzantion* 50 (1980): 410–38, with full bibliography of sources and literature at 410–12; for the background and context, see J. F. Haldon, "Approaches to an Alternative Military History of the Period ca. 1025–1071," in *The Empire in Crisis? Byzantium in the Eleventh Century (1025–1081)*, ed. E. Chrysos (Athens, 2003), 45–74, with literature. The logistical considerations discussed here also were reviewed in J. F. Haldon, "La logistique de Mantzikert," in *Guerre et société, Byzance–Occident (VIIIe–XIIIe siècle)*, ed. D. Barthélemy et J.-C. Cheynet, Centre de recherché d'histoire et civilisation de Byzance, Monographies 31 (Paris, 2010), 11–25. For the older literature, see esp. S. Vryonis, *The Decline of Medieval Hellenism in Asia Minor and the Process of Islamization from the Eleventh through the Fifteenth Century*, rev. ed. (Berkeley, 2011), 71–76 with notes, 494–97; idem, "The Greek and Arabic Sources for the Battle of Mantzikert, 1071 A.D.," in *Byzantine Studies: Essays on the Slavic World and the Eleventh Century*, ed. S. Vryonis, Jr. (New York, 1992), 125–40; and idem, "A Personal History of the History of the Battle of Mantzikert," in *Το εμπόλεμο Βυζάντιο = Byzantium at War*, ed. N. Oikonomidès (Athens, 1997), 225–44. See also the account in A. Friendly, *The Dreadful Day: The Battle of Manzikert, 1071* (London, 1981). For events following the capture of the emperor Romanos IV by the Seljuk leader, see S. Vryonis, Jr., "The Greek and Arabic Sources on the Eight-Day Captivity of the Emperor Romanos IV in the Camp of the Sultan Alp Arslan after the Battle of Mantzikert," in *Novum Millennium: Studies on Byzantine History and Culture Dedicated to Paul Speck*, ed. C. Sode and S. Takács (Aldershot, 2001), 439–50.

12 On communications networks in Anatolia, see J. Koder, "Regional Networks in Asia Minor during the Middle Byzantine Period: An Approach," in *Trade and Markets in Byzantium*, ed. C. Morrisson (Washington, D.C., 2012), 147–75; for pack animals and wheeled vehicles, see R. W. Bulliet, *The Camel and the Wheel* (Cambridge, Mass., 1975).

13 For the physical evidence, see, for example, P. Gazzola, *Ponti Romani*, vol. 2, *Ponti Romani, Contributo ad un indice sistematico con studio critico bibliografico* (Rome, 1963); C. O'Connor, *Roman Bridges* (Cambridge, 1993); and for roads and road surfaces, see

except where the terrain was unsuitable, with a central spine and a fairly uneven surface of comparatively small stones, and many of these show clear evidence of wheeled vehicles.[14] And although, according to Procopius, Justinian made efforts to improve several important roads,[15] it appears that roads maintained after the sixth century were generally narrow and often stepped in mountainous stretches, a development that dates from the mid- or later sixth century. There are three clear examples: the road from Antioch to Beroea and Chalkis in northern Syria; the road from Tarsus to the Cilician Gates, along a surviving section near Sağlıklı; and the Via Sebaste through the Döşeme pass from Pamphylia to Lycia. The last named provides a clear illustration, with up to four layers of pavement from consecutive repairs or partial rebuildings; the earliest observable stratum dates to the Via Sebaste, built by Augustus in 6 BC. This road was more than 6 meters broad, with a wheel-rutted but irregular surface. It seems to have been completely rebuilt in the early Byzantine period and was used, with further repairs that cannot be accurately dated, until the late Ottoman period. But the late Roman road was much narrower (no more than ca. 3.5 m wide), and on steeper inclines it was stepped. The edges are made of comparatively large blocks, with the carriageway itself of smaller blocks, laid more carefully than the Roman surface, although not as regular as other examples of road surfaces that can be dated to this period.[16] And while the surfaces of the other two roads dated to the early Byzantine period are slightly different, they too have steps in most of their ascending sections. Similar observations have been made regarding the Via Egnatia, which was likewise rebuilt on a much narrower plan with a smoother surface, and stepped in some sections.[17]

We should not therefore conclude that wheeled traffic was impossible, however, since in most cases the "steps" are in fact very shallow and may be assumed to permit some types of vehicle, if not too heavily laden, to be pulled up and over them; they would certainly permit a measured descent. Nevertheless, the evidence does suggest that pack animals, where possible, remained the chief means of transporting most goods across long distances. When heavy equipment, such as might be required for a siege train, had to be carried, then wagons and carts were employed. Depending on the terrain, wagons or carts could act as a considerable brake; thus the *Taktika* of Leo (although repeating the *Strategikon* of Maurice at this point) notes that on occasion infantry units accompanied by baggage animals with provisions for eight to ten days might be sent on ahead.[18] But this was not always the case, and under optimal conditions a two-wheel mule-drawn cart could cover as much as 30 kilometers per day; an ox-drawn four-wheeled vehicle, between 15 and 24 kilometers per day.[19] Attaleiates informs us that units of "Scythian" (i.e., Pecheneg) cavalry were sent out ahead of the main columns. In the Mantzikert campaign Romanos clearly had his siege equipment transported this way—Attaleiates mentions that he had up to a thousand carts or wagons bearing the artillery and other devices (which in single column would have stretched along some 9.5 kilometers of road or track); and just as during Manuel I's campaign against Konya in 1176, for example, when a siege train consisting of large numbers of wagons accompanied

Koder, "Regional Networks in Asia Minor during the Middle Byzantine Period," 155–52, with fig. 6.6 and further literature.

14 See D. H. French, "The Roman Road-System of Asia Minor," in *Aufstieg und Niedergang der Römischen Welt* 7.2 (Berlin, 1980), 698–729 at 703–4, 713; idem, *Roman Roads and Milestones of Asia Minor*, vol. 1, *The Pilgrim's Road*, BAR International Series 105 = British Institute of Archaeology at Ankara Monograph 3 (Oxford, 1981), 19–22.

15 Cf. Procopius, *Buildings* 4.8, 4–9; 5.2, 6–8, 12–14; 5.5, 1–3, ed. H. B. Dewing (Cambridge, Mass.–London, 1940), 284–86, 324, 336.

16 D. H. French, "1989 Roma Yolları Miltaşları ve Yazıtları Araştırması," *Araştırma Sonuçları Toplantısı* 8 (1990): 229–40, esp. 233–35; and idem, "A Road Problem: Roman or Byzantine?" *IstMitt* 43 (1993): 445–54, esp. 448.

17 Cf. French, "A Road Problem," 449.

18 Leo VI, *Taktika*, ed. G. T. Dennis, *The Taktika of Leo VI: Text, Translation and Commentary*, CFHB 49 = DOT 12 (Washington, D.C., 2010), vi, 24.

19 Roth, *The Logistics of the Roman Army*, 208–12; see also B. S. Bachrach, "Animals and Warfare in Early Medieval Europe," in *L'Uomo di fronte al mondo animale nell'alto Medioevo*, Settimane di Studio del Centro Italiano di Studi sull'alto Medioevo 31, Spoleto 1983 (Spoleto, 1985), 707–51. See especially the discussion in Belke, "Verkehrsmittel und Reise- bzw. Transportgeschwindigkeit," 54–55, specifically with regard to the Mantzikert campaign. Belke notes that the ox- or mule-drawn carts carrying the siege train were unlikely to have accompanied the army along the whole 1,500 km of the route from Bithynia to Mantzikert, but would have been drawn from regional resources once the army reached Theodosiopolis, where the emperor is known to have stopped for a longer pause in the march (Attaleiates, *Historia*, 148–49).

Table 1. Feed requirements and loads

FEED	Hard fodder (kg)	Dry/green fodder (kg)	Pasturage (kg)	Water (L)
Donkey	1.5	5.0	10.0	20
Mule	2.0	6.0	12.0	20
"Pack animal"	2.0	5.5	11.0	20
Horse	2.2	7.0	14.0	30
Ox	7.0	14.0	22.0	30

LOADS[a]	Man + military equipment/clothing (kg)	Saddle (kg)	Pack saddle (kg)	Load (kg)	Total (kg)
Horse[b]	70 + 30	12	--	--	112
Pack horse	--	--	16–19	96	112–115
Mule	--	--	16–19	96	112–115
Donkey[c]	--	--	16–19	64	80–83
Wagon (4-wheel), 2/4 oxen	--	--	--	650/1000	650/1000
Cart (2-wheel), 2 mules	--	--		500	500

a. The figures for animal loads must be taken as approximations to within 1 or 2 kg.
b. Cavalry mounts could carry additional loads without suffering harm, but only very small amounts—ca. 4 kg, sufficient for three or four days' supplies for the trooper, or about one day's worth for both himself and his mount (the late sixth-century *Strategikon* and the tenth-century treatise *Skirmishing* recommend that cavalry soldiers carry three to four days' supply with them in their saddlebags): see Maurice, *Strat.* 1.2.4; *Skirmishing* §16. For wagon and cart loads, see Bachrach, "Animals and Warfare in Early Medieval Europe" (n. 18 above), and Roth, *The Logistics of the Roman Army* (n. 4 above), 208–12.
c. Ancient figures suggest a load two-thirds that of a mule.

the army, the main columns must have been considerably slowed if, as seems to have been the case on both occasions, the main body of the army and the siege train marched together.[20] Crusader armies marched along the Via Militaris across the Balkans with their carts, but Crusader sources describe stretches of this road as by turn rocky and mountainous or swampy, where wheeled transport became a clear hindrance.[21]

From the middle of the seventh century onward, a clearly defined system of predominantly military routes evolved, along which imperial and provincial marching camps were established. A similar pattern also emerged in the Balkans, although without the marching camps; and in both cases, the new emphasis reflects a specifically Byzantine strategic response to invasion, while relying on an existing Roman network. Although direct evidence is sparse, the situation of many settlements and the continued occupation of most late Roman urban sites, even if much reduced, suggest that the roads of the late Roman period continued in use, in spite of their gradual dilapidation, at least until—as happened in the sixth century to the stretch of the Via Egnatia described above—they became so potholed and irregular that even pack animals and soldiers could not pass. Since their maintenance was localized and infrequent, by the sixth and seventh centuries many must have become little more than paths or tracks

20 For Romanos's siege train, see Attaleiates, *Historia,* 151.12–15; and for the advance units, 148.18–20. For 1176, see *Nicetae Choniatae Historia,* ed. J. A. Van Dieten, CFHB 11 (Berlin, 1975), 179.

21 See K. Belke, "Roads and Travel in Macedonia and Thrace in the Middle and Late Byzantine Period," in *Travel in the Byzantine World,* ed. R. Macrides, Society for the Promotion of Byzantine Studies 10 (Aldershot, 2002), 73–90, at 76–79, with sources.

unsuitable for any wheeled vehicles at all, although the upkeep of major routes does appear to be attested archaeologically.[22]

The support required for such forces has rarely, if ever, received any scholarly attention, but in fact the logistical requirements were huge. Whether the estimates often given for Romanos's army are plausible is not really important here, since our aim is simply to present some idea of the needs of the army along its marching route. It is possible to establish basic requirements for soldiers, cavalry mounts, and pack animals or draft animals, using figures from both Roman and Byzantine sources as well as comparative statistics from later, but still premodern and preindustrial, sources.[23] Although there remains a small margin of error, table 1 sets out basic requirements for men and animals in an army such as that mustered by Romanos IV for the Mantzikert campaign.[24]

With these statistics at our disposal, we can then proceed to a calculation of how much food, fodder, water, and so forth is required for a given number of soldiers and animals in an army (or any other body). Here, simply to illustrate the nature of the logistical problem faced by armies, we have limited the data involved to food/provisions only, for men and beasts; a more complex calculation would also entail data for equipment, spare weapons, siege artillery, and so forth. To carry out the calculation we can use a simple equation, as follows:

$$N = \frac{(a + b + c + d)\,y}{(x - z)\,y}\text{, where}$$

N = the number of mules required
a = the sum of the soldiers' provisions (food only; kg)
b = the sum of the horses' rations (kg)
c = the sum of the rations of the pack mules (kg)
d = the sum of the rations of the remounts that also carry provisions (kg)
x = the average load carried (kg)
z = the standard ration of the animals carrying the provisions (kg)
y = the duration of the expedition (days)[25]

As an example, let us calculate the requirements for a small cavalry force of 1,000 men, accompanied by 250 spare horses, to see how many pack animals would have been needed. They require 1,000 × 1.3 kilograms (for the soldiers) + 1,250 × 2.2 kilograms (for the horses) per day: that is, 1,300 + 2,750 = 4,050 kilograms per day.[26] We can then multiply this sum by the number of days, and divide by the weight in kilograms carried by each pack animal, minus its own daily ration, to see how many pack animals would be required. Needs are calculated only up to the twenty-fourth day, since the tenth-century evidence suggests that troops after that length of time could no longer rely on supplies brought with them but would have to forage locally, unless they also had wagons to carry provisions. Assuming that the remounts carry no provisions, table 2 shows the results.

If provisions were carried on the 250 remounts, each horse would carry some 68 kilograms (× 250), making a total of 17,000 kilograms.[27] Both men and horses could be maintained for up to four days from these supplies; at the same time, the soldiers could carry up to four days' supplies for themselves, or a day's worth

22 For a good overview of the Roman road system in Asia Minor, see the map edited by W. M. Calder and G. E. Bean, *A Classical Map of Asia Minor* (London, 1958). For a discussion of the Byzantine material, see K. Belke, "Von der Pflasterstrasse zum Maultierpfad? Zum kleinasiatischen Wegenetz in mittelbyzantinischer Zeit," in *Byzantine Asia Minor (6th–12th cents.),* ed. N. Oikonomides (Athens, 1998), 267–84; and idem, "Communications: Roads and Bridges," in *OHBS,* 295–308.

23 For human nutritional requirements under varying conditions, as well as those of animals, together with further information on marching and carrying capacities, see (in addition to the literature cited below) Erdkamp, *Hunger and the Sword* (n. 3 above), 27–45, 62–83.

24 For the sake of the illustration, we repeat here parts of the discussion on the logistics of late Roman and Byzantine armies in J. F. Haldon, *Warfare, State and Society in the Byzantine World, 565–1204* (London, 1999), 158–74, 281–92. Estimates of loads vary among authorities—between 85 kg and 114 kg, depending on the period and stature of the animal. Based on middle Byzantine evidence, we will take an average load for mules and pack horses to be 96 kg. See ibid., 282–83, for figures and evidence.

25 For this equation, see Engels, *Alexander the Great and the Logistics of the Macedonian Army* (n. 4 above), 22 and n. 35.

26 For figures for soldiers' rations and horses' requirements, see Haldon, *Warfare, State and Society in the Byzantine World,* 167–69, 287, with sources and literature.

27 For these figures, see detailed discussion in ibid., 169, 288.

Table 2. The requirements for 1,000 cavalry, accompanied by 250 spare horses

1 Number of days	2 Total weight of provisions (kg)	3 Load minus ration per animal (kg)	4 Total no. of mules required	5 No. of mules no longer needed, per day
1	4,050 × 1 = 4,050	÷ (96 − 2.2 × 1)	= 43 (40)[a]	1 (1)
2	4,050 × 2 = 8,100	÷ (96 − 2.2 × 2)	= 88 (83)	2 (2)
5	4,050 × 5 = 20,250	÷ (96 − 2.2 × 5)	= 238 (220)	6 (5)
10	4,050 × 10 = 40,500	÷ (96 − 2.2 × 10)	= 547 (500)	12 (10)
15	4,050 × 15 = 60,750	÷ (96 − 2.2 × 15)	= 964 (864)	22 (18)
20	4,050 × 20 = 81,000	÷ (96 − 2.2 × 20)	= 1,558 (1,446)	35 (30)
24	4,050 × 24 = 97,200	÷ (96 − 2.2 × 24)	= 2,250 (1,900)	51 (39)

a. The figures in parentheses in columns 4 and 5 represent the effect of a lower estimate for hard fodder requirements and a conservative estimate for loads. See Roth, *The Logistics of the Roman Army at War* (n. 4 above), 206–7.

of supplies for themselves and their mounts, extending this initial period to some five days at the outside.[28] With the additional provisions carried on 1,523 mules, they could provide themselves with food to last about twenty-four days altogether.

This offers some idea of a method for calculating requirements. If we accept that the Mantzikert army numbered 60,000 at the most, as noted already, then its requirements for food will have been as follows, for the men alone:

$$60{,}000 \times 1.3 \text{ kg per day} = 78{,}000 \text{ kg per day}$$

We do not know how many of this army were cavalry, but if we assume a ratio of 20 percent, as was standard for all armies in this period, then we also need to calculate for some 12,000 horses (12,000 × 2.2 kg per day = 26,400 kg per day). Let us take a very conservative estimate of a further 25 percent of this figure for remounts—that is, 3,000 × 2.2 kilograms = 6,600 kilograms—making a total for the 15,000 horses of 33,000 kilograms per day. In addition, each horse would require about 14 kilograms of pasturage and some 30 liters of water per day. This basic requirement for green fodder per horse amounts to some four to five hours of grazing per twenty-four hours; thus 20 horses will graze out 1 acre (0.4 ha) of medium-quality pasture per day (on campaign, less). The 15,000 horses we have assumed thus far would thus require some 450,000 liters of water and 210,000 kilograms of green fodder, equivalent to 750 acres (300 ha) of medium pasture, every day. While armies on the march were frequently supplied below optimal levels, the figures we have employed here are minima, below which the army would rapidly have lost cohesion and effectiveness.

But in addition to the soldiers and their mounts, of course, there were also pack animals. In imperial territory the army would clearly have obtained much of its supplies through the established means: local officials would arrange for the appropriate foodstuffs to be made available along the route, either by filling warehouses or by allocating a specific burden of provisions to each village.[29] This appears to have been the system used throughout the march from Bithynia as far as Theodosiopolis (Erzerum), an inference supported by the hints in the sources at conflicts between the indigenous provincial populations during the march eastward. Elsewhere the army would, as far as possible, forage off the land—the division sent on to Khliat, for example, supplied itself from the local harvest, which predictably created a shortage of supplies for the besieged garrison and population.[30] At Theodosiopolis

28 *Skirmishing* §16, ed. and trans. G. T. Dennis, in *Three Byzantine Military Treatises*, CFHB 25 = DOT 9 (Washington, D.C., 1985); cf. Maurice, *Strat.* 1.2.4, 81.

29 For a detailed account, see Haldon, *Warfare, State and Society in the Byzantine World*, 139–48, 171–72.

30 Attaleiates, *Historia*, 150.7–12.

the emperor issued orders to the remaining troops to forage and to collect two months' worth of supplies, in view of the lack of forage along the road to Mantzikert and its environs.[31] It will be worth looking at how those commands affected the size of the army, on the one hand, and the localities through which the army was passing, on the other.

Using a recent estimate of the forces at the emperor's disposal,[32] we have some 60,000 men plus animals: a total of 15,000 horses, with various permutations on these figures if we include oxen and wagons. Two months' provisions for the men would amount to 60,000 × 1.3 kilograms per day of basic rations = 78,000 kilograms per day, multiplied by—let us say—60 days (the two months of the emperor's orders). The total of weight in provisions—wheat, in this case—for the soldiers alone, without ancillary attendants or animals, would thus amount to some 4,680,000 kilograms, or 4,680 tonnes (about 4,606 tons). For the sake of the example, let us also assume that enough green fodder and forage was available along the route that none would have to be added to the supplies carried by the animals (it is not clear from the sources that this was actually the case). Assuming this quantity of materials could be located, what would be required to transport it over the two months in question?

Calculations at this level become more conjectural. For example, we have no idea whether the soldiers themselves carried a certain proportion of their rations—in the Roman army in the first and second centuries, for example, each legionary soldier was supposed to carry up to 20 days' worth of rations for himself (which would total some 1,248,000 kg for the 48,000 foot soldiers of this army). There is little evidence that Byzantine soldiers were either trained or able to undertake such self-provisioning, although they probably did so on occasion. But let us assume, again for the sake of this example, that the situation in which Romanos's army found itself was one such occasion, that the remounts also carried a full load of supplies (3,000 × 68 kg = 204,000 kg), and that each cavalryman carried the maximum possible weight in supplies (4 kg per man, to last 3–4 days: 12,000 × 4 kg = 48,000 kg). The maximum that could thus be transported by men and horses amounts to 1,500,000 kilograms of the army's total requirements (fighting men only) of 4,680,000 kilograms, leaving some 3,180,000 kilograms to be carried by pack animals or on wagons. While, as we have said, we know that the Mantzikert army was accompanied by carts carrying the siege train, we have no idea whether carts were also employed for supplies. For the sake of the argument and to illustrate the numbers entailed, we will, for the moment, leave wheeled vehicles out of the equation and assume that the material was carried by mules and pack horses alone.

We then apply the simple formula given above. The result is that in order to transport the full load of 3,180,000 kilograms for two months (both for the march to Mantzikert and for the first weeks in the area), and again assuming that all the feed for such animals could be found by foraging, an army of 48,000 infantry and 12,000 cavalry would need more than 33,000 beasts of burden—an amazingly large number of animals, although not impossible under the right conditions. We may adjust the figures somewhat by assuming that the animals could be overloaded, perhaps by as much as 20 percent, as was often the case with military pack animals; and we can increase the number of remounts taken along by about 100 percent. This might reduce the need for additional animals to some 25,000 or so. Even at half the daily ration per man allowed above, a level hinted at in one source for expeditionary forces[33] (and which assumes that the soldiers were able to supplement that very meager ration from the land they passed through), the numbers are impressive, and we must ask whether a Byzantine army could have had access to 12,500 pack animals, let alone 25,000. The density of mules and horses in the regions in question per square kilometer in the 1930s—when the conditions associated with a traditional pastoral and agrarian economy still obtained in these regions and when the population was substantially greater than in the eleventh century—varied from between 2–3 to 4–6.[34] Collecting as many as 15,000 draft or pack animals along the route followed by the army in 1071, or at any other time in the eleventh century, would have greatly challenged the resident population along

31 Attaleiates, *Historia,* 148.14–17. For Leo, see *Taktika,* vi, 23.

32 Cheynet, "Mantzikert," 426.

33 See Leo, *Taktika,* vi, 24, and commentary in Haldon, "Roads and Communications in the Byzantine Empire," 147.

34 See Great Britain, Royal Navy, Naval Intelligence Division, *Turkey,* Geographical Handbook Series, B.R. 507, vol. 2 (London, 1943), 171–72, and fig. 47.

a corridor 80 kilometers wide for a distance of at least 320 kilometers. The demand for pack animals for two months for an army of 60,000 even under the conditions we have assumed above would thus appear to have been beyond the capacity of the land or economy of the areas through which the army was to pass. Of course, we can alter the proportion of pack animals to supplies by assuming that supplies were also carried in carts or wagons, as prescribed in the *Strategikon* of Maurice and repeated in the *Taktika* of Leo VI.[35]

We could considerably reduce the number of mules, for example, if we assumed that the army was accompanied by, say, 1,000 carts, each carrying some 650 kilograms of supplies: thus, we could transfer some 650,000 of the required total of 3,180,000 kilograms mentioned above, thereby reducing the number of mules or pack horses by about a fifth (although we would then have to take into account the feed and other requirements for the draft animals, in this case oxen). We might further alter the balance by assuming that where wheat or grain for bread was hard to acquire, and where substantial numbers of livestock were driven along with the army for the soldiers to consume, the ratio of bread to meat shifted (in which case the impact on the health of the soldiers of this shift in dietary regime also needs to be written into the equation). That it was indeed a standard practice for most large armies to keep livestock on the hoof is clear from the mid-tenth-century treatise on imperial military expeditions, and Attaleiates remarks on the vast herds of livestock—probably sheep—accompanying the army on the Mantzikert campaign after its stop at Theodosiopolis.[36] But the method is unlikely to have substantially reduced the numbers of pack animals required.

Yet all this remains in the realm of the hypothetical—we continue to lack hard factual data on the size of the army, the number of livestock it required, the number of ancillary personnel that accompanied it, the feeding routine for the animals (crucially, whether they were largely grass-fed and put to pasture during such a campaign, which would dramatically reduce the total provisions required), and so forth. And we can argue in circles about the probability or plausibility of these figures by drawing comparisons with similar situations in earlier or later societies, similar landscapes, and so forth. Is it possible to narrow the range of interpretational possibilities open to historians in this context? And if it is, what sort of options are available?

To put these requirements in a comparative context, we may note that the average size of major Ottoman expeditionary armies campaigning against the Safavids around 1600 was never higher than 50,000–70,000 and was usually smaller;[37] moreover, the population of Asia Minor under the Ottomans, upon which this level of mobilization of manpower relied, was about 7 million.[38] The resource base in terms of agricultural produce and the ratio of producers and townspeople to soldiers was therefore clearly much greater then than in the Byzantine world in the eleventh century (despite the relatively crude statistical basis for such generalizations), when a population of perhaps 4.5 million may be assumed (based on projections back from Ottoman registers and taking into account a general demographic upturn in the twelfth–thirteenth centuries, the effects of the Black Death, and the period of recovery that followed, ca. 1480–1520).[39]

What about the capacity of the landscape to deliver this amount of provisions? Foraging parties can travel only a limited distance from the main army and still remain in sufficient contact to supply it—a corridor 80 kilometers wide, which would give mounted foraging parties considerable leeway in their efforts to locate supplies, has been mapped onto the plan of the route, as seen above in figure 1, though in reality foraging in the northern section beyond Sebasteia (Sivas)

35 But see Belke, "Verkehrsmittel und Reise- bzw. Transportgeschwindigkeit," 55.

36 See Constantine Porphyrogenitus, *Three Treatises on Imperial Military Expeditions,* ed., trans., and comm. J. F. Haldon, CFHB 28 (Vienna, 1990), text (C), 146–47, and commentary at 202, where sheep, lambs, cattle, and calves are listed; for Mantzikert: Attaleiates, *Historia,* 151.15–17.

37 Murphey, *Ottoman Warfare, 1500–1700* (n. 4 above), 41, 48–49. For the effects of predatory foraging on local populations within Byzantine territory, see discussion, with sources and further literature, in Haldon, *Warfare, State and Society in the Byzantine World,* 170–71, 235–43.

38 H. Inalcık, *An Economic and Social History of the Ottoman Empire,* vol. 1, *1300–1600* (1994; reprint, Cambridge, 1997), 25–29.

39 For general trends throughout this period, see references in n. 3 above, and B. H. Slicher van Bath, *An Agrarian History of Western Europe* (London, 1963); for the impact of these changes on Byzantium, see A. Harvey, *Economic Expansion in the Byzantine Empire, 900–1200* (Cambridge, 1989), 244–63; and for the situation in Ottoman Asia Minor from the fourteenth century on, see Inalcık, *An Economic and Social History of the Ottoman Empire,* 1:25–32.

through which the army had just marched would have been restricted by the mountains of the Pontic range and then the Armenian highlands. The quantity of produce required for the two months mentioned in the sources—some 4,680 tonnes (4,606 tons)—would have required an area of between 595 and 648 square kilometers (230–250 square miles = 147,000–160,000 acres = 59,500–64,800 ha), judging from the rates of production of these areas in the 1920s. The rates in the eleventh century may have been lower, though perhaps on average higher in the most fertile grain-producing regions. In any case, and keeping in mind that these figures are entirely hypothetical, foraging from such an area will have required the dispatch of the tens of thousands of pack animals already calculated to areas some distance away from the line of march, a process that explains their relatively slow progress.[40]

The question of whether the landscape through which such a large army would have passed could support these additional demands is very difficult to answer. To establish the details of this logistical operation more exactly we need information about land use and levels of agrarian productivity—information that, unfortunately, hardly appears at all in Byzantine texts. But there is comparable information from other parts of Europe for that period and, more importantly, from the same areas for other times, particularly the early modern period. It therefore should be possible, taking into account changes in agricultural technology where appropriate, as well as changes in crop types and land use, to work out some idea of where and in what quantities Byzantines produced grains, for example, and what might have been available to support transient populations such as armies. An important, indeed crucial, difference has been noted concerning the source of supplies: an army traveling through its own country will, at least in theory (a point frequently emphasized in Hellenistic, Roman, and Byzantine military treatises), wish to take only a very small proportion of the total available foodstuffs from the producers so that they might have sufficient resources for the rest of the year, whereas in enemy or hostile territory much more can be taken (assuming that the region has not already been depleted by armies and warfare). Of course, such distinctions were by no means always observed, and the impact on the "home" population could often be severe, as many contemporary sources note. Paul Erdkamp comments, for example, that a rural population will normally need to produce enough food to support itself over twelve months. Most of this will result from one or two harvest seasons, and will thus need to be stored. Such stored resources would, in theory, be sufficient to maintain an army twelve times the size of the producing population for one month, if that army arrived immediately after the harvest; but of course seizing all available resources would lead to the starvation of the resident populace. While this action might have been appropriate in enemy lands, it was clearly not possible on home territory, where only a much smaller percentage of the harvest could be taken—and even then the producing population might suffer harm. These kinds of problems that face a transient military force as well as the resident population need to be built into any analysis, along with many other factors that must be taken into account.[41]

It is possible to set out some broad guidelines. For example, historians have established some relationships between cultivated area and yield that can help us establish how much land (of appropriate quality soil), cultivated by how many man-days of labor, would be required to provide the sort of provisions we have been discussing. There are several problems of methodology here, of course. Ancient sources were not interested in the sort of data we seek. Land itself does not have a fixed capacity; its production depends on the amount of labor invested and the techniques and crops used. Sowing rates vary, and returns on seed vary by season,

40 See Erdkamp, *Hunger and the Sword,* 122–40; and for comparative discussion for later periods, see G. Perjés, "Army Provisioning, Logistics and Strategy in the Second Half of the Seventeenth Century," *Acta Historica Academiae Scientiarum Hungaricae* 16 (1970): 1–51; J. A. Lynn, "Foods, Funds and Fortresses: Resource Mobilization and Positional Warfare in the Campaigns of Louis XIV," in *Feeding Mars: Logistics in Western Warfare from the Middle Ages to the Present,* ed. J. A. Lynn (Boulder, Colo., 1993), 137–59; see also the discussion in Van Crefeld, *Supplying War* (n. 4 above); and G. Parker, *The Military Revolution: Military Innovation and the Rise of the West, 1500–1800* (Cambridge, 1988). In a longer-term perspective, the patterns and fluctuations in annual production, harvests, crop failure, and so forth will also need to be taken into account: see, for example, P. Garnsey, *Famine and Food Supply in the Graeco-Roman World: Responses to Risk and Crisis* (Cambridge, 1988), for detailed discussion of both the evidence and the ways in which the issues can be modeled and analyzed.

41 See Erdkamp, *Hunger and the Sword,* 18–20, with further literature.

by year, by type of soil, and by levels of fertility. High seed-sown:seed-yield ratios are often accompanied by low returns per unit area. In addition, it has been observed that for a subsistence peasant farmer there is no normal seed-sown:seed-yield ratio—sowing rate, type of soil, amount of seed stored from previous years, numbers of available agricultural workers, and so forth all affect levels of production. We might also add that demands from landlords or governments similarly affected this picture, since levels of yield might be forced upward—subject to the constraints of crop and climate—by economic and political pressures.[42]

A range of proposals for ancient cereal yields have been made, largely based on Roman evidence from Italy, Greece, and similar Mediterranean contexts, but still useful here as a broad illustration. One researcher suggests a figure for wheat of 390 kilograms per hectare (156 kg per acre),[43] which represents a seed-sown:seed-yield ratio of 1:3, at a sowing rate of 130 kilograms per hectare (52 kg per acre), and for barley of 670 kilograms per hectare (268 kg per acre), in a seed-sown:seed-yield ratio of 1:5 with the same sowing rate.[44] An ancient source proposes 600–900 kilograms per hectare (or 240–360 per acre) for wheat, with a seed-sown:seed-yield ratio of 1:5–7, at a sowing rate of 130 kilograms per hectare, and 1,020–1,270 kilograms per hectare (or 408–508 per acre) for barley, with a seed-sown:seed-yield ratio of ca. 1:7–9, at the same sowing rate.[45] These figures are based on an inscription from Eleusis, dated to 329/28 BCE, that records the receipt by officials of the sanctuary of the first fruits in wheat and barley for the ten tribes of Attica, together with a series of deductions about cultivated area, fallow regime, and so forth. They therefore can be, and have been, challenged on a number of grounds. More recent estimates based on the same inscription combined with archaeological and survey information have produced the following figures:

> Wheat: 625 kg/ha (or 250 kg/acre);
> seed-sown:seed-yield ratio of 1:4.8;
> sowing rate of 130 kg/ha (or 52 kg/acre)
>
> Barley: 770 kg/ha (or 308 kg/acre);
> seed-sown:seed-yield ratio of 1:6;
> sowing rate of 130 kg/ha[46]

From the medieval period we have slightly different calculations, varying as well according to terrain, but producing an average yield for wheat of some 1:3.3 on the plain and 1:2.8 on higher arable river terraces.[47] We will take a reasonable mean between these figures of some 1:4 for wheat, with a per hectare production of about 520 kilograms (i.e., 208 kg/acre) and a sowing rate of 130 kilograms per hectare (52kg/acre), and retain the estimate of 770 kilograms per hectare (i.e., 308 kg/acre) for the barley, so that we can begin to make some calculations about the amount of land required to produce supplies for the forces used in our examples. Although recent research in this field suggests that these yields are comparatively low, they are borne out by the very limited (textual) evidence currently available for the late Roman and Byzantine periods. Here, documents relating to crop yields for both the Balkans and Asia Minor suggest returns on sowing of some 1:3.5–5 in ground of medium quality and in dry conditions, with higher rates in wet or irrigated areas—as much as 1:8–9.[48] But since yields in Italy in the later medieval and early modern periods range from 1:3–4 to 1:8–10, and in pre-1940s Turkey from 1:5 to 1:9, depending on zone (wet or dry), we may take our proposed figures as averages across a wider terrain with an assumed range

42 There is a large literature on this topic. See A. Jardé, *Les céréales dans l'antiquité grecque: La production* (1925; reprint, Paris, 1979); P. Garnsey, *Cities, Peasants and Food in Classical Antiquity: Essays in Social and Economic History* (Cambridge, 1998); P. Halstead, *Traditional and Ancient Rural Economy in Mediterranean Europe* (London, 1987); and S. Isager and J. E. Skygaard, *Ancient Greek Agriculture: An Introduction* (London, 1992). On seed:yield ratios, see M. S. Spurr, *Arable Cultivation in Roman Italy, c. 200 B.C.–100 A.D.* (London, 1986); and P. Garnsey, "Yield of the Land," in *Agriculture in Ancient Greece*, ed. B. Wells (Stockholm, 1992), 147–55.

43 One hectare = 10,000 m² or 2.471 acres, though given the relative imprecision of these values, we have rounded the latter figure up to 2.5 for ease of reference.

44 A. Barbagallo, "La produzione media relativa del cereali e delle vite nella Grecia, nella Sicilia e nell'Italia antica," *Rivista di Storia Antica* 8 (1904): 477–504.

45 Jardé, *Les céréales dans l'antiquité grecque*, 33–60.

46 Garnsey, *Cities, Peasants and Food in Classical Antiquity*, 201–13.

47 Spurr, *Arable Cultivation in Roman Italy*.

48 E. Patlagean, *Pauvreté économique et pauvreté sociale à Byzance, 4e–7e siècles* (Paris, 1977), 246–48; M. Kaplan, *Les hommes et la terre à Byzance du VIe au XIe siècle: Propriété et exploitation du sol* (Paris, 1992), 80–82.

of variable subareas; they therefore can serve our purpose, if only as illustrations of the issue at hand.[49]

The number and complexity of the factors that must be taken into account in any attempt to narrow down the range of possibilities for the size of a medieval field army make the requisite calculations enormously complicated. It is thus natural to design a computer model into which information about the productive capacity of the landscape, numbers of soldiers and animals needed, carrying capacities, speed of movement, and distances covered for foraging can all be fed to produce a general estimate of logistical requirements under a range of different conditions, as the calculations use different sets of data that reflect the variations in the textual, archaeological, and environmental evidence. Since these data require access to appropriate types of evidence—including archaeological data on settlement patterns and related information from palynology, dendrochronology, and stable isotope analysis, as well as historical (textual) evidence for land use, levels of return on seed sown, and so forth—the picture will remain incomplete except in those areas where such information can be obtained or at least modeled on the basis of historically viable parallels. Before we can even begin to think about actual historical cases and real numbers, therefore, we need a great deal more information about the area or areas where such an army operated. We need to know about the soil and its ability to support different types of agricultural or pastoral activity; we need to know about climate and seasonal variations; and we need to know about long-term alterations in climate over time in order to take account of changes or fluctuations in productivity, density of population, and so forth. In addition, we need to know about the size of the resident population at the time in question, and thus about fluctuations in numbers over time; we also need to know something of the ways in which produce and livestock were moved around to understand what the logistical possibilities for a particular culture at a given time actually were.[50] And all of these details need to be understood within the context set by a particular culture and its ways of doing things.

Major landscape survey projects and the application of environmental methodologies have recently begun to provide a detailed landscape and settlement context for some regions (including approximations of settlement systems and landscape productivity). Within certain limitations, these areas can now offer an appropriate backdrop for models that approximate military behavior, with site catchment analysis and soil mapping, along with cost-surface modeling, playing an important role. In mapping the routes of armies across the land, we must also confront a variety of related issues. How far did soldiers forage, and under what conditions, to locate sources of food for themselves and their animals? Since foraging is necessarily restricted by, on the one hand, the relationship between energy investment and economic return and, on the other hand, the distance covered in the process (modified by other factors such as strategic necessity, demand for movement at a certain average speed, and so forth), those factors can also be modeled and written into any broader framework for assessing logistical requirements and structures.[51]

Formal modeling of military activity is quite common; battlefield scenarios are frequently associated with, for instance, variations on combat or game theory. However, sophisticated analyses of logistical behavior are virtually absent from the literature for medieval military history, and those discussions that do exist often rely on comparisons with later armies or on data for completely unrelated campaigns. The Medieval

49 M. Aymard, "Rendements et productivité agricole dans l'Italie moderne," *Annales: Économies, Sociétés, Civilisations* 28 (1973): 456–92; G. Hillman, "Agricultural Productivity and Past Population Potential at Aşvan: An Exercise in Calculation of Carrying Capacity," *Anatolian Studies* 23 (1973): 225–44.

50 On medieval animals and their requirements and carrying capacities, see Bachrach, "Animals and Warfare in Early Medieval Europe"; and W. C. Schneider, "Animal laborans: Das Arbeitstier und sein Einsatz im Transport und Verkehr der Spätantike und des frühen Mittelalters," in *L'Uomo di fronte al mondo animale nell'alto Medioevo* (n. 19 above), 457–578.

51 See, for example, V. Gaffney and Z. Stančič, *GIS Approaches to Regional Analysis: A Case Study of the Island of Hvar* (Ljubljana, 1996); V. Gaffney, Z. Stančič, and H. Watson, "Moving from Catchments to Cognition: Tentative Steps toward a Larger Archaeological Context for GIS," in *Anthropology, Space and Geographic Information Systems*, ed. M. Aldenderfner and H. D. G. Maschner (Oxford, 1996), 132–54; and Z. Stančič, V. Gaffney, K. Ostir-Sedej, and T. Podobnikar, "GIS Analysis of Land-use, Settlement Patterns and Territories on the Island of Brac," in *Archaeological Applications of GIS: Proceedings of Colloquium II, UISPP XIIIth Congress, Forli, Italy, September 1996*, ed. I. Johnson and M. North, Sydney University Archaeological Methods, Series 5 (Sydney, 1997).

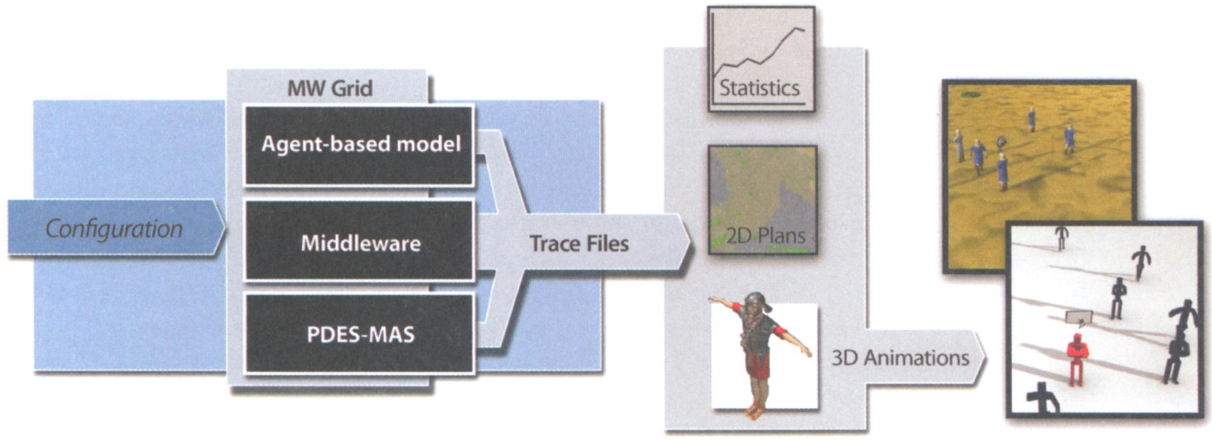

FIG. 2. The MWGrid framework

Warfare on the Grid (MWGrid) project is developing an agent-based model of the Byzantine army's march to Mantzikert to provide insight into how tens of thousands of people, horses, and mules along with tons of equipment were transported well over 1,100 kilometers through the Anatolian summer. By modeling different scenarios based on historical records and modern interpretations of how the Byzantine infrastructure supported an army on campaign, we aim to draw valuable conclusions regarding how the systems of transportation, taxation, agricultural production, and military organization were interconnected. The project centers on agents representing all the members of the army. From the commander down to the lowliest servant, all parts of a military structure share one clear goal: to arrive at a destination in a fit state to win a battle.[52] They act as part of a hierarchical organization but have a certain amount of autonomy in their decision-making, and they travel through an environment that contains a variety of resources needed to complete their journey. Multiple executions of the agent-based model are required, with inputs of different numbers of people and animals, different levels of food availability, and different types of organization and route planning. The simulation will record both the state and progress of the army, as well as how communities were affected by the army's progress. To model an army of between 40,000 and 70,000 people with attendant horses and pack animals on a one-to-one basis requires more than 100,000 agents. Clearly, the processing power and the memory needed for this simulation far exceed the capabilities of any single computer making sequential calculations: the only viable approach is to use distributed simulation and harness distributed computing resources. But it must be emphasized at the outset that a model is not reality—it merely allows us to limit the range of historical possibilities and to generate a range of explanatory scenarios.

The framework designed for the project is provided in figure 2. It can be seen as consisting of two major parts: the simulation system and the analysis environment.

The simulation system executes the model and produces detailed trace files that are fed into the analysis system for later, off-line processing. The range of packages used in such processing depends on the output required. Statistics can be produced that detail movement rates, food consumption, the health status of agents, the amount of time spent on the move, and the state of the environment after the army has moved on; they can pertain to individual agents, to certain subgroups, or to the whole army. It is also possible to import a transformed trace file into a three-dimensional modeling package and thereby automatically create a 3-D visualization. Being able to display the results of the model in a 3-D representation is important for communicating the output of traditional agent-based

52 While it is true that the Byzantine armies in particular attempted to wear an enemy down rather than throw themselves into a full-scale field engagement, and that most medieval warfare involved maneuvering and attacking resources in manpower, livestock, and agrarian produce rather than battlefield conflict, it is also the case that in this particular campaign Romanos's intention was indeed to confront the Turks and engage them in a decisive battle.

modeling. Three-dimensional representations have their dangers, however, as they are so inherently persuasive that they can convey an artificial sense of authority; but the ability to produce different representations of the model's results remains useful in interpreting and explaining those results.

The simulation system consists of three layers: the agent-based model (ABM), the distributed simulation kernel (PDES-MAS, or "parallel discrete event simulation of multi-agent systems"), and the "middleware," which functions as an interface between the two. The middleware, using a number of specific interfaces, clearly describes ways in which the ABM interacts with PDES-MAS. It is also the framework that supports the ABM; for example, it provides a scheduler (a system that appropriately orders the jobs to be done by the computer) and a distributed object class (a mechanism that enables software modules residing in different computers to work together) that can be extended into an agent.[53] The computer model that runs on this framework also consists of two main elements: the environment, representing the terrain, infrastructure, and resources of Anatolia, and the agents, representing the human and animal members of the Byzantine army on a one-to-one basis.

The Analysis Environment

Eleventh-century Anatolia represents a large and rich environment for an agent-based model: Mantzikert is more than 1,100 kilometers from Constantinople as the crow flies, and the intervening terrain is varied. There is, however, no direct route: on the available roads of the period the army actually had to march a further 400 kilometers or so to arrive at its objective. Abstracting the relevant data at an appropriate scale is an important part of preparing the environment, which is represented in a series of slices. Each slice deals with a different aspect of the Anatolian landscape and can be represented either as an array of values covering the whole of the ABM area or as a list of locations with associated values, used for sparse data sets.

Each cell of the environment is approximately 5 square meters, giving a total size of 280,700 × 88,890 cells. However, the area covered is so large that representing it in simple geographical data formats—for instance, the Esri ASCII array that is standard for encoding geographical information into a file that can then be processed by a computer—would require a file size of around 140 gigabytes. For this reason, two larger resolutions were supported within the model for environmental data, 50 and 500 square meters, and these provided files of manageable size (1.4 GB and 14 MB, respectively). This is permissible because high-resolution data are required only to accurately model specific activities, not to merely describe the environment. Because the project is primarily concerned with practical aspects of feeding and moving the army, only certain characteristics of the historical environment are relevant to the model: specifically, terrain, roads, settlements, land use, and water.

Terrain

The physical geography of Anatolia plays a large part in the planning of the army's route. The nature of the terrain will affect movement rates: broken ground will force the army into narrower columns, and tight mountain passes may even require it to move in single file. Terrain also affects the energy expended during movement, which in turn determines how much food and water are consumed. Since the shape of the Anatolian terrain has not changed significantly in the past 900 years, the use of modern data will not significantly affect the model's accuracy. The highest-quality terrain data available to the project are the ASTER Global Digital Elevation Model (GDEM) data (fig. 3), from a satellite mapping project jointly undertaken by NASA and Japan's Ministry of Economy, Trade and Industry.[54] They consist of height data in cells approximately 30 meters square, which are converted into an Esri ASCII array with cells 50 meters square in order to fit more conveniently into the MWGrid environment. Because terrain is a continuous data set, it is stored in a large raster file (1.4 GB unzipped, 275 MB zipped) with a 28,070 × 8,889 resolution. Because only a small part of these data is required at any given time, the model splits

53 B. G. W. Craenen and G. K. Theodoropoulos, "Interfacing Multi-agent Models to Distributed Simulation Platforms: The Case of PDES-MAS," in *Proceedings of the 2010 Winter Simulation Conference*, ed. B. Johansson, S. Jain, J. Montoya-Torres, J. Hugan, and E. Yücesan (Baltimore, 2010), 587–94 (also accessible at http://informs-sim.org/wsc10papers/prog10.html).

54 ASTER stands for "Advanced Spaceborne Thermal Emission and Reflection Radiometer," a Japanese sensor on NASA's Terra satellite, launched in 1999.

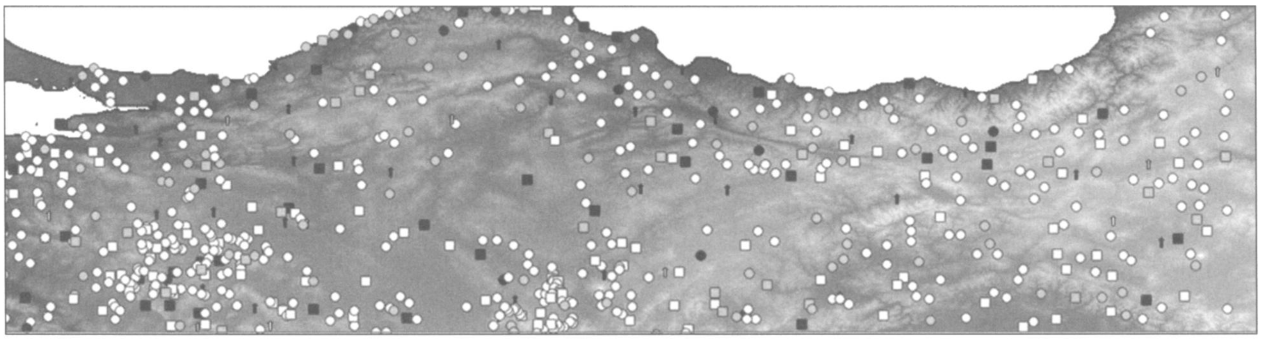

FIG. 3. Settlements and terrain data (from NASA Jet Propulsion Laboratory, California Institute of Technology, www2.jpl.nasa.gov/srtm/), with settlements characterized by type, corresponding to those in the *TIB* maps: black = walled settlement, gray = citadel settlement, and white: unfortified settlement; tower = archbishopric, square = bishopric, and circle = no ecclesiastical status

the data into partitions, which are loaded and discarded as required.

Roads

Roads obviously facilitate both faster movement and more convenient routes. Although the Byzantine road system was a degraded version of the earlier Roman infrastructure, it still offered a faster and more reliable option than trekking across country.[55] Within the MWGrid model, roads are represented as a sparse data set, stored efficiently because the location of cells is recorded only where roads are present. At a resolution of 50 square meters, the resulting file is around 3 megabytes. The *Tabula Imperii Byzantini* (*TIB*) maps give locations for roads for part of the area,[56] but there are difficulties in extrapolating known data to fill in any gaps. Unlike settlements, which are discrete data points, roads are linear features that actually lead from somewhere to somewhere, often by a meandering route. This unpredictability makes them harder to generate plausibly. For that reason, only major routes are plotted outside the coverage of the *TIB* maps—but since the army is likely to have followed major routes, this limitation should not affect the overall accuracy of the model.

Settlements

As mentioned above, the army was supplied with food and equipment by the communities through whose territories it passed. Specific settlements were places to be visited along the march in order to pick up necessary supplies. Generally situated near water sources, they served as purveyors of news, local guides, entertainment, and souvenirs or loot for the campaigning soldiers. They therefore are important for the route planning and provisioning elements of the model. Size is also an important factor, as larger settlements will have been the collecting point for larger areas and will thus have amassed more supplies.

In the model each settlement has an associated food surplus that is affected both by its surrounding landscape and by the seasons. The availability of grain is a factor often considered by planners of military campaigns throughout antiquity, and the amount of the surplus varies considerably throughout the year.[57] To facilitate this calculation, settlements are not merely static points with set amounts of resources, but are defined as a special type of agent in order to take advantage of each tick (step) of the simulation to update each type of resource as availability changes throughout the year.

As they do for roads, the *TIB* maps provide settlement data for some areas. On the basis of the density of different types of settlement in the *TIB*-covered area, random points can be selected outside this area to

55 French, *Roman Roads and Milestones of Asia Minor* (n. 14 above); Koder, "Regional Networks in Asia Minor during the Middle Byzantine Period," 152–55.

56 H. Hellenkamper and F. Hild, *Lykien und Pamphylien, TIB* 8, DenkWien 320 (Vienna, 2004).

57 Engels, *Alexander the Great and the Logistics of the Macedonian Army* (n. 4 above).

create a reasonably plausible distribution of settlements. The *TIB* maps also separate settlements into various categories that can be assigned population values; combined with research related to rural productivity, these provide some indication of how much surplus food is available at each location.

Land Use and Climate

Recent work on the palaeoclimatic situation in Anatolia over the past two millennia has considerably advanced our knowledge of what Byzantine armies would have confronted during the period with which this article is concerned. It is therefore now possible to model the climatic conditions in approximate terms, especially with regard to rainfall patterns, and thus to model as well the adequacy of water supplies and other resources, including agricultural produce, for a transient population such as an army for the Byzantine period.[58] These data—which can themselves be varied to offer a range of possible climate scenarios—will form part of the contextual information built into the model described here.[59]

The transport of goods across Anatolia was expensive due to the distances involved, making the types of resources available to each settlement dependent on local conditions. The produce available at each settlement varied according to regional agricultural practice, which in turn depended largely on the nature of the surrounding landscape. The primary types of food available to the army were grain and meat, and the availability of each has profoundly different implications for the movement and provisioning of the army. Grain was the staple food of antiquity, mainly in the form of bread, which formed a significant part of the ancient diet. Because bread is both perishable and bulkier to transport than the grain itself, military units carried hand mills to grind their own grain and make their own bread. Meat too is perishable, and must be preserved to last any significant time, but it can be transported on the hoof. Reliance on live animals adds to the problems of moving the army because of its increased size, but this food effectively transports itself. The animals would be driven along with the army until needed, then butchered and consumed.[60]

Each foodstuff affects the movement of the army in different ways, and the differing availability of each type of food across Anatolia would have affected the army's progress in ways that cannot be accurately predicted in advance. Any attempt to tailor the resources available at each settlement to what each produced requires numerous assumptions. We lack sufficient evidence about rural food production to put together a complete and convincing model of which types of agriculture were practiced in the many different environments of Anatolia. For now, modern land use remains the best guide, as this is partly determined by climate and terrain, both of which, again, have altered relatively little since the eleventh century, despite significant cultural and technical changes. A comprehensive reconstruction of the flora, fauna, and agricultural practices of Byzantine Anatolia is beyond the scope of this project.

The data on modern land use employed in the project were supplied through the European Space Agency's GLOBCOVER (i.e., global land cover) satellite program.[61] They break down land use into a series

58 See the literature on ancient food production cited above in nn. 40–47.

59 See M. D. Jones, C. N. Roberts, and M. J. Leng, "Quantifying Climatic Change through the Last 21,000 Years in Central Turkey Based on Lake Isotope Palaeohydrology," *Quaternary Research* 67 (2007): 463–73; R. Touchan, U. Akkemik, M. K. Hughes, and N. Erkan, "May–June Precipitation Reconstruction of Southwestern Anatolia, Turkey during the Last 900 Years from Tree Rings," *Quaternary Research* 68 (2007): 196–202; M. D. Jones, C. N. Roberts, M. J. Leng, and M. Türkeş, "A High-Resolution Late Holocene Lake Isotope Record from Turkey and Links to North Atlantic and Monsoon Climate," *Geology* 34 (2006): 361–64; and A. England, W. J. Eastwood, J. F. Haldon, C. N. Roberts, and R. Turner, "Historical Landscape Change in Cappadocia (Central Turkey): A Palaeoecological Investigation of Annually-Laminated Sediments from Nar Lake," *The Holocene* 18.8 (2008): 1229–45, at 1232–33, 1240. For the longer-term picture with important implications for Anatolian climatic fluctuations between the Roman and medieval periods, see also M. Magny, O. Peyron, E. Ortu, G. Zanchetta, B. Vannière, and W. Tinner, "Contrasting Patterns of Precipitation Seasonality during the Holocene in the South- and North-Central Mediterranean," *Journal of Quaternary Science* (2011), at http://onlinelibrary.wiley.com/doi/10.1002/jqs.1543/abstract.

60 On Byzantine logistics and military supplies, see Haldon, *Warfare, State and Society in the Byzantine World* (n. 24 above), 166–76, 281–86; and idem, "Chapters II, 44 and 45 of the *Book of Ceremonies:* Theory and Practice in Tenth-Century Military Administration," *TM* 13 (2000): 201–352, at 294–98.

61 See P. Bicheron, P. Defourny, C. Brockmann, L. Schouten, C. Vancutsem, M. Huc, S. Bontemps, M. Leroy, F. Achard, M. Herold, F. Ranera, and O. Arino, *GLOBCOVER: Products Description and Validation Report* (Toulouse, 2008).

of categories that can be converted into likely eleventh-century production zones. To be sure, determining the amount of surplus produce available to specific communities remains problematic, as there are insufficient data to generate a comprehensive or plausible solution, but competing hypotheses can be tested with the model. Moreover, though the information from ancient and medieval sources is sparse, enough can be gleaned to establish not just approximate zones of cultivation but even a range of parameters for levels of productive output.[62] Because fine detail is unnecessary for such information, the data can represented at a relatively coarse resolution of approximately 500 square meters per cell.

Water

Availability of water is the single most important issue for an army, since without it no military force can survive for long, especially in a relatively arid environment. It is clear that Byzantine armies campaigned along routes whose potential access to water was, in many cases, well-known, and it is certain that Romanos's campaign route was largely predicated on such information. But as is true of land use, ascertaining the distribution of water resources remains problematic and the differences between modern and ancient environments remain unclear; some areas, especially where the modern Turkish state has dammed rivers to supply irrigation and hydroelectric power, without question have changed significantly since the eleventh century, yet there is little alternative but to use modern data. These data do have the benefit of containing flow rates, which cannot be known for the eleventh century (even if a map of Byzantine Anatolian rivers existed) and which provide information on seasonal water availability. In addition, since none of the rivers of Byzantine Anatolia was navigable in the area covered by the ABM, the only effect of water on an army's movement is to reduce its speed when it crosses larger watercourses.

The Agents

The granularity and complexity of individual agents are dictated by the project's goals. Medieval military leaders understood the practical problems involved in moving large numbers of people across broken terrain and through narrow ravines, and grasped the enormous effect of terrain on an army's progress. Average movement rates have been calculated for armies based on historical itineraries; and while determining the relationship between army size or composition and rate of march remains problematic,[63] this is one aspect that the model is ideally suited to address. With that in mind, we have decided to model the people and pack animals of the army at a ratio of one agent per human or animal. Doing so will result in a more convincing model of crowd movement and will simplify the modeling task, as there will be no need to decide how to aggregate several individuals into one agent.

Agent Architecture

An agent is a software object that possesses a series of characteristics, properties, and behaviors. Each such agent consists of a plan queue, a messaging queue, and a representation of a perception base, along with a number of private and public variables modeling agent characteristics (for an example, see fig. 4). The plan queue contains a list of the tasks that the agent has to perform. The message queue contains a list of messages from other agents, including orders from superiors and messages from comrades. The perception base contains the information possessed by the individual agent about the world, including information gathered by the agent's own senses and information introduced by communication with other agents.

Each agent has a series of variables, depending on its type. These are dictated by the need to model the organization of the army, its movement, and the effects of the march on each individual agent. An agent's variables can be public (those that are apparent to other agents, such as health and location) or private (e.g., speed, vision range). It can perform range queries to access the public variables of every agent within a certain distance. Orders are given when another agent passes on a message whose content is an order. Provided that the message comes from a valid source (a superior or a trusted comrade), the content of the message is added to the agent's plan queue.

The organization of the Byzantine army provides a rigid hierarchy into which the agents can fit (fig. 5). The

62 H. Goodchild, "Modelling Agricultural Production: A Methodology for Predicting Land Use and Populations," in Haldon, *General Issues in the Study of Medieval Logistics* (n. 4 above), 199–228, and the discussion above.

63 See Haldon, *Warfare, State and Society in the Byzantine World,* 158–66.

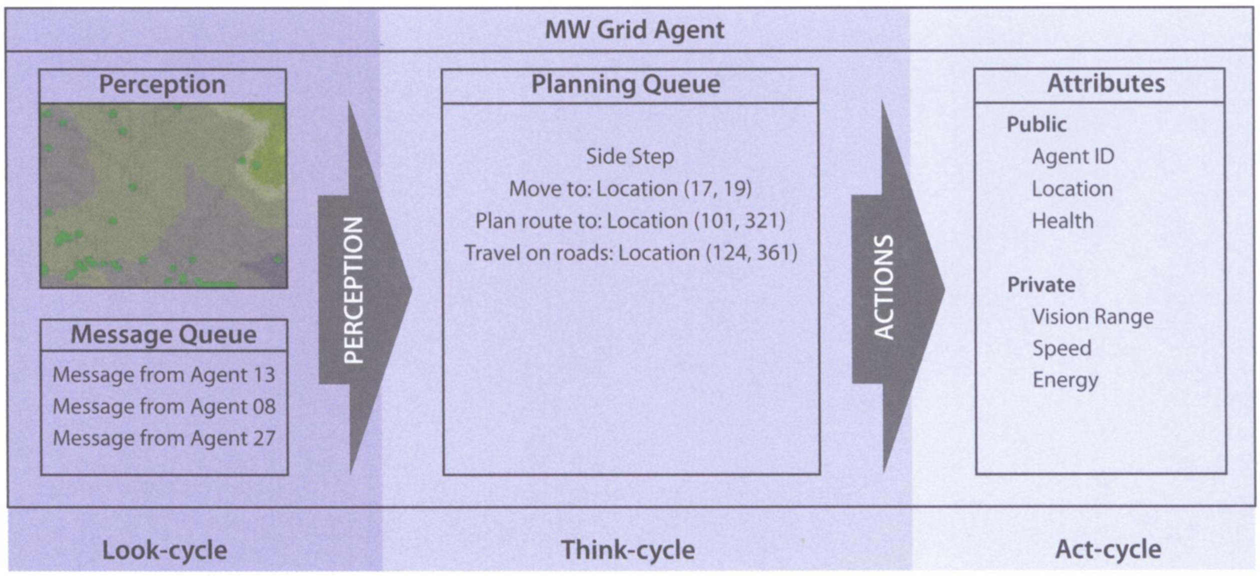

FIG. 4. The MWGrid agent

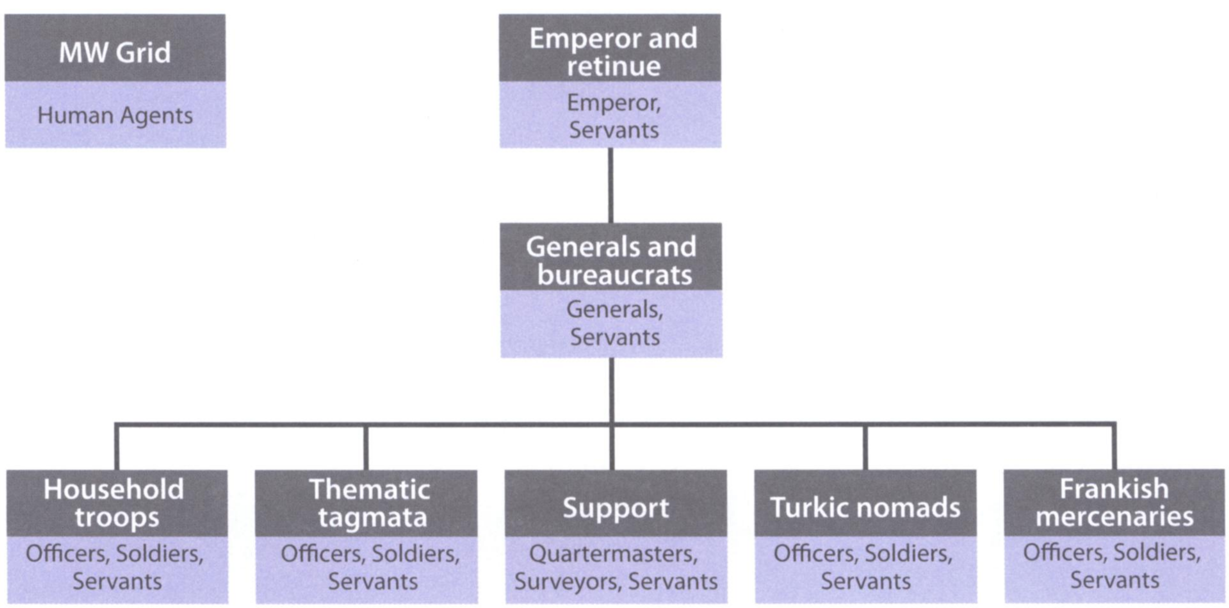

FIG. 5. Organization of agents

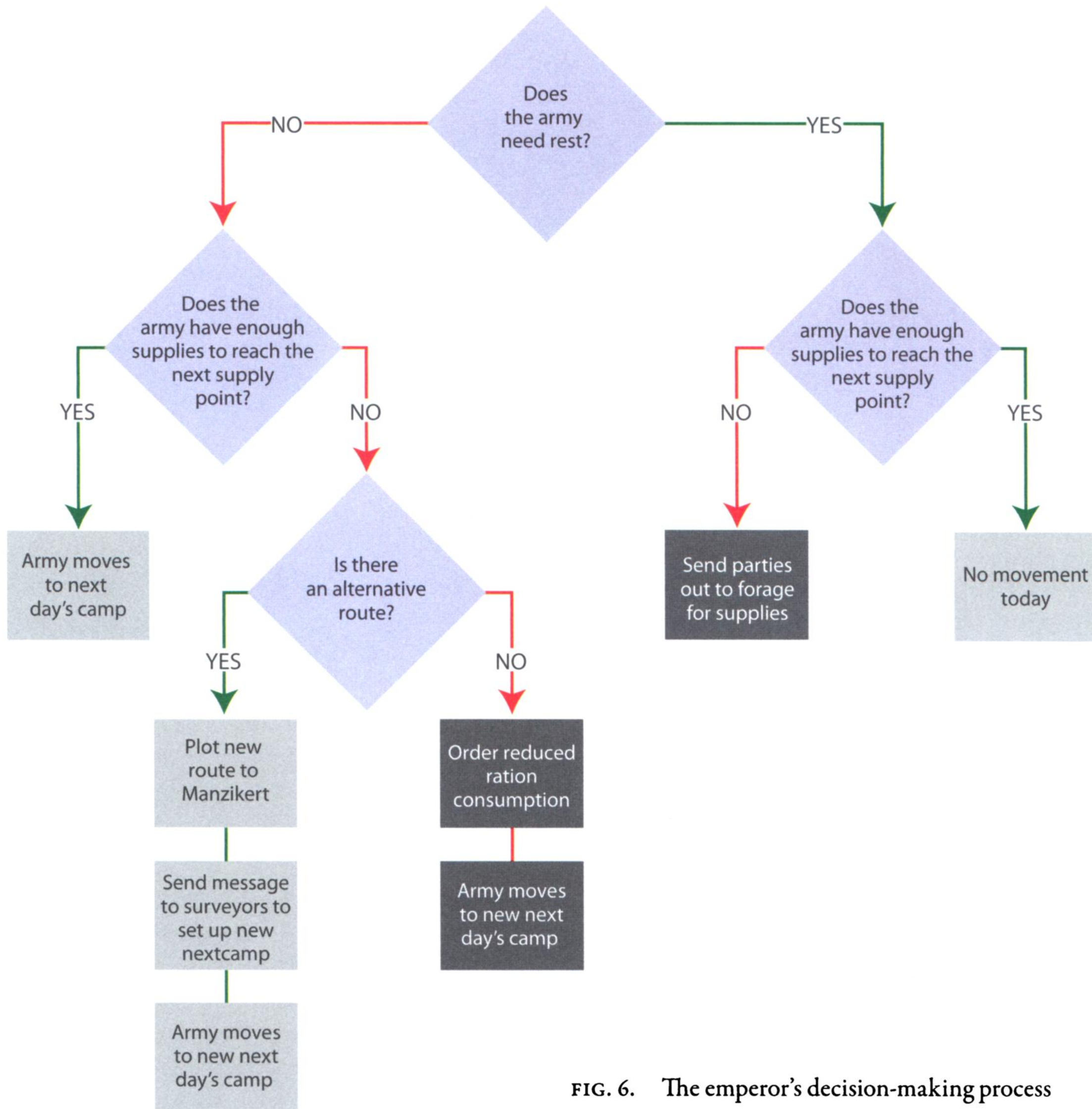

FIG. 6. The emperor's decision-making process

emperor occupies the apex of the pyramid and decides which route to take (fig. 6).[64] His order to move, along with the location of the next day's camp, will be propagated down the command structure until it reaches the officers of each individual squad.

Agents lower in the hierarchy are required to make fewer decisions. The main task of each agent is to transport itself and any equipment it is responsible for from the previous camp to the next one. Once at the camp some soldiers, primarily from the lower-status thematic troops, will be tasked with digging a bank and ditch around the camp; others will ensure that their unit has sufficient supplies, to be collected from their unit's baggage train. The camp will have been deliberately sited near a water source, if possible, to ensure a decent supply each day and to avoid the need to transport large quantities of water between camps.

64 Of course, this structure is an ideal type—it is well established that social organizations, both large and small, tend to be both mutable and flexible within the limits set by their social-functional roles and context. For the purpose of modeling the relationship between physical environment and agents, however, an "averaged" structure is perfectly adequate. In addition, it should be understood that the various agents in the command structure—"the emperor," "an officer," and so forth—represent systemic relationships as much as they represent individuals: the functions attributed to them are themselves "typical" in the sense of the aims of the model.

The command structure of the army again is useful for regulating behavior, as resources flow up and down between baggage handlers at both unit and squad level, and information on the scarcity of a particular resource or group of resources flows up to those responsible for organizing resupply.

Movement

The movement of the army and its individual agents is a critically important part of the model. The model specifically aims to help assess how large numbers of individuals' micro-level movements affect the macro-level movement of the army. Determining their interactions and their repercussions on the environment through which the army passes is the central thrust of the project. This distinction between the macro-level movement of the army and the micro-level movements of the individuals within it is reflected in the systems designed to facilitate the army's movement.

The emperor will have decided on a route in advance of the campaign, a normal procedure that allowed the areas being passed through enough warning to stockpile the supplies required to feed and equip the army. The planning of the overall route depended on ease of movement and the availability of supplies and the settlements in which to store them. This aspect of planning is dealt with by a modification of standard probabilistic roadmap (PRM) movement. In standard PRM movement, a random pattern of nodes is created over the environment and edges are created between them.[65] Agents can plan routes and move between nodes along those edges. Thus the process of navigating across large numbers of individual cells becomes considerably easier, as route-planning decisions are made from node to node rather than from cell to cell. In the MWGrid ABM, the random pattern of nodes is replaced by the pattern of settlements, reflecting the army's need to move from settlement to settlement to pick up resources and take advantage of water sources.

Once an overall route is planned by the emperor, the individual agents can use a route-planning algorithm to navigate between waypoints.[66] The movement of an army on the march is not a disorganized free-for-all, however; it needs to have some regularity to avoid chaos and to ease departure from camp in the morning and arrival at the new camp in the afternoon. To this end, the order to move is propagated out among the unit leaders in a set sequence, each one setting off only after the previous unit has left. Individual squad soldiers follow their leader using flocking behaviors.[67]

Planning

Each agent has a plan queue in which an agent's designated tasks are stored in the order in which they need to be performed. The current plan to be executed consists of a series of actions. Plans further down in the queue consist of one symbolic action, which is expanded into a series of appropriate actions when it is executed (fig. 7).

If these subsequent actions need to be revised, the action queue can be cleared back to the original first action and then expanded again. Doing so is useful if, for example, an agent seeking to pick up a resource creates a plan to move to the nearest occurrence of that resource, and then finds that someone else has taken the resource in the interim. In this case, all subsequent actions can be cleared and the original action can be reprocessed, so that the next nearest resource can be found. This planning process is well-suited to the limited number of actions required. The planning is highly logistical: most of the tasks involve moving somewhere and interacting with some environment object. With the addition of a "priority" attribute and a "plan to execute in event of failure" in each plan, each agent should have enough information to be able to prioritize its own tasks and react to their consequences, including failure, in an intelligent way.

The scenarios we wish to model as part of the Byzantine army's march across Anatolia can be modeled with relatively basic object-handling plans (Collect Resource, Pick Up Object, Drop Object), basic message-passing instructions (Give Order, Request Information,

65 L. E. Kavraki, P. Svestka, J. C. Latombe, and M. H. Overmars, "Probabilistic Roadmaps for Path Planning in High-Dimensional Configuration Spaces," *IEEE Transactions on Robotics and Automation* 12.4 (1996): 566–80.

66 P. E. Hart, N. J. Nilsson, and B. Raphael, "A Formal Basis for the Heuristic Determination of Minimum Cost Paths," *IEEE Transactions on Systems Science and Cybernetics SSC4* 4.2 (1968): 100–107.

67 C. W. Reynolds, "Flocks, Herds and Schools: A Distributed Behavioral Model," *Computer Graphics* 21.4 (= *SIGGRAPH '87: Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques*) (July 1987): 25–34.

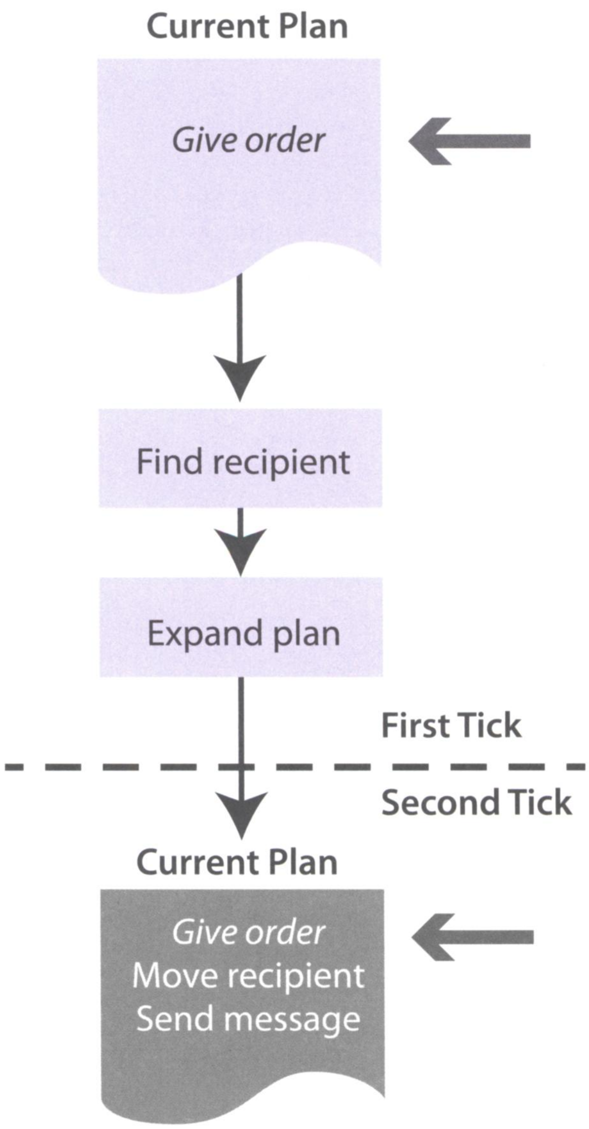

FIG. 7. The expansion of a plan into a series of actions

Pass Message), and some plans referring to specific situations that arise during the army's march (Set Fire, Set Up Tent, Dig Ditch, Patrol). Owing to the limited number of plans required and the restricted set of circumstances in which they will be used, this approach does not unreasonably increase the time needed to program the model, even though the process of performing tasks is largely hard-coded.

Messaging

Communication is critical when an army moves. All agents in the army must have an appreciation of where they are in the army's organizational structure. They must know who their superiors are and who is under their command. They must also know the rank of all other agents. In this way an agent can prioritize messages received from other agents. Each message consists of the Agent ID of the sender, the Agent ID of the intended recipient, and the content itself. Content can be a piece of information about the environment, some information about another agent, or an order. It is placed in the recipient's message queue to await processing. On being processed, either the information is added to the agent's perception base or the order (if from a valid source) is added to the agent's plan queue.

Orders are propagated down the chain of command until they reach the intended recipient. Information is also contained in messages and can be filtered up the chain of command to the emperor. For the emperor to know whether the army needs to rest or to forage for supplies, he must gather information from the units and the quartermasters about the status of the provisions. The information exchange within an army is relatively tightly constrained: a soldier who discovers that his squad lacks food reserves will not take this information straight to the emperor but will instead inform his superior, who will in turn do the same, until the information reaches the decision makers.

Middleware

Interaction between the ABM and PDES-MAS is handled by the middleware layer of the framework. Time in a MWGrid simulation is partitioned into discrete "time-steps," which are maintained by the scheduler. During each time-step, the scheduler initiates a routine of action for each agent in the simulation. This routine is captured by the look-, think-, and act-cycle of the agent (see fig. 4). During the look-cycle, the agent senses its environment and reads its messages from the message queue. Sensing takes the form of using range queries to read public variables for all agents. In the think-cycle the messages read from the message queue will be interpreted and the plan queue updated. The resulting action in the act-cycle is expressed either by writing public and private variables of the agent itself or by sending messages to other agents. The simulation

ends when the allotted time-steps have run out and the step-method of all agents has been called for each of these time-steps.

The simulation itself implements an update method that functions by turning internal data in the simulation into external data in the form of a trace file. The trace file is then used in subsequent processing to produce statistics, as well as two- and three-dimensional representations or animations of the simulation (see also fig. 2). In order to complete this process, the scheduler initiates the routine of action in each time-step, thereby providing read access to all agents in the simulation.

A Simple Example

The computational requirements to run the MWGrid army are substantial, and the team is beginning to scale up the experiments only now, as this article goes to press. The first results demonstrate the issues related to moving the large group of men making up the army. Within the model, they cross terrain extracted from the Anatolian digital elevation model and move from a designated starting point to a designated destination (see fig. 8). The model simply seeks to measure what the scale of impact may be when the army's size increases.

The graph in figure 9 shows the average travel time for each of the men in a group of ten squads, in ticks (steps of the simulation). The emperor orders each squad leader to a point outside the camp, then to a point just outside the following day's camp, then to a specific location within that camp. Since the squads keep the same relative positions in each night's camp, all squads must travel about the same distance. The emperor moves in front and therefore is barely affected by the increase in number of squads. As a consequence, his arrival time in the next camp increases by no more than 15 ticks regardless of the number of squads in the model. As can be seen from the graph, the increase in travel time is irregular and unpredictable, varying from squad to squad. Crowding leads to an increasing divergence in arrival times, as certain squads get caught up in traffic while other squads avoid significant delay. Delay occurs mainly at the point outside the first camp where the squads gather before setting off for the following camp. Because they arrive at roughly the same time, considerable shuffling of personnel may be necessary before everyone can set out on the route to the next camp.

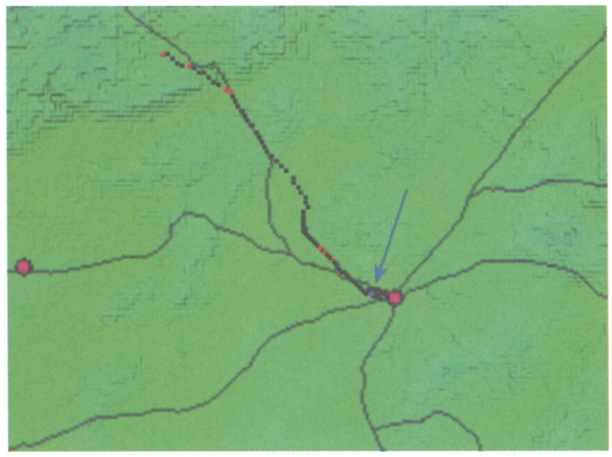

FIG. 8. The army moving between two fixed points: the black points represent soldier agents; the red points, leaders; and the blue point (indicated by arrow), an emperor; the image, taken from an early movement test of the simulation, is modeled on a landscape near Ankara and is not to scale.

The Promise of Modeling

As pointed out above, we do not mean to suggest that historians should become computer scientists; rather, it is our contention that in some cases historical and archaeological data alone can take us only so far as we attempt to understand certain sets of events or developments. In some of those cases, as in this investigation of logistics, numbers, and resources, it is possible to bring history and computer science together in a way that sheds light on areas far beyond the immediate question addressed. So we have approached the issue of medieval logistics from two different but complementary perspectives. On the one hand, we have shown that even after carefully accounting for the relevant manpower and livestock requirements, together with road and communications infrastructure, the data are insufficient to support more than a series of plausible estimates. Such estimates can vary dramatically, and each can be challenged by individual historians who have different ideas, based on comparative statistics and historical examples, of what is reasonable. On the other hand, we have described a large-scale agent-based model, designed to study medieval military logistics, and have employed a key series of historical events, constituting the Mantzikert campaign, as a case study.

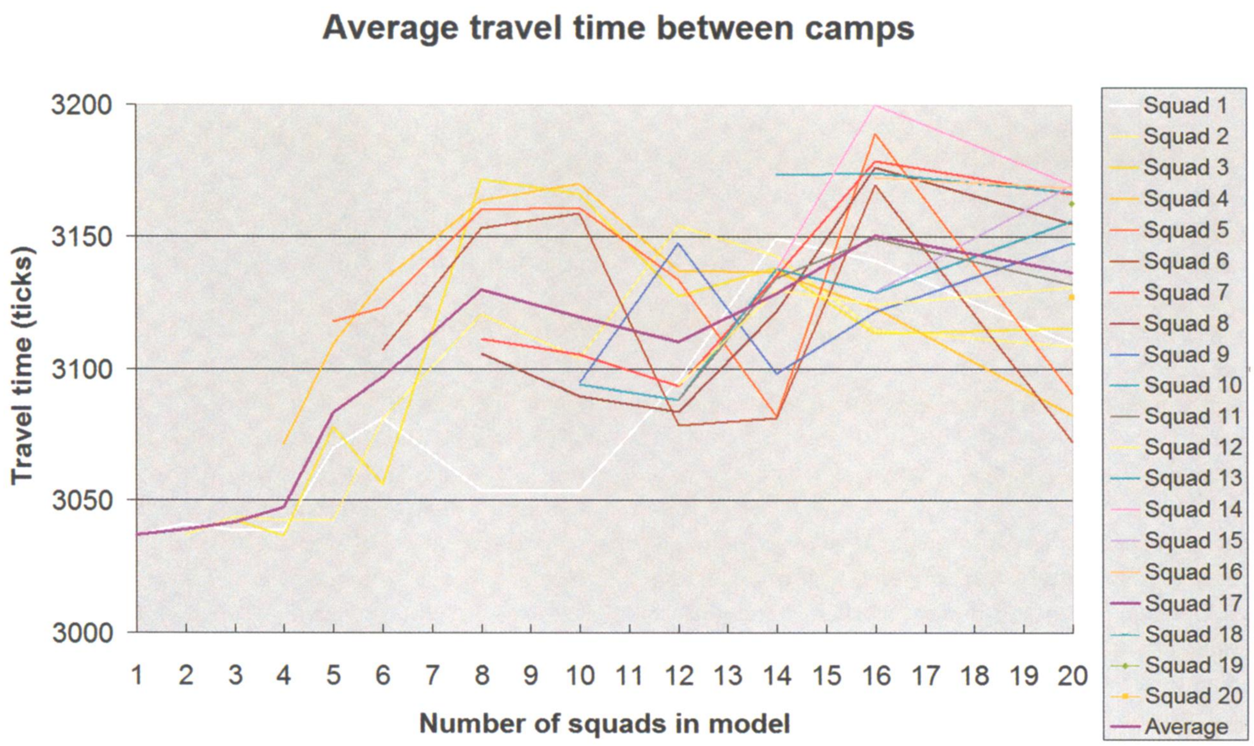

FIG. 9. Movement of 10 squads and incremental change (scenarios were not run for squads 7 and 9)

Historical sources for the Mantzikert campaign give numbers for the size of the Byzantine army that are inflated or, at best, highly problematic und uncorroborated; the result, as noted, is that historians, who agree that the sources are unreliable, are unable to find evidence for even the range of possibilities. The model addresses precisely these fundamental uncertainties, in particular the question of how many people could be transported across Anatolia and under what circumstances. While previous work has relied on average rates of movement,[68] the model examines the relationship between army size and speed of movement, and it can help us determine the amounts of agricultural surplus required for armies of differing sizes in a particular historical landscape. Different patterns of agricultural production can be tested against different conjectures of army size and movement to help eliminate implausible scenarios. Some patterns of agricultural production may result in a surplus insufficient to support even a modest army. Some army sizes may be unsupportable under even the most optimistic assumptions. Modeling these scenarios with different sizes of army and levels of food availability may lead us to conclude that some interpretations derived from historical sources are actually impossible.

From the point of view of computer scientists, the development of models of such scale and complexity presents both opportunities and important challenges: What agent architectures are appropriate to capture the essential characteristics of the problems and support the required scenarios? What is an appropriate model of distribution for models with such behavioral characteristics? As the infrastructure described in this article nears its full development and integration, we will begin to provide some answers to the above questions and evaluate the suitability and performance of our approach. From the point of view of historians, modeling the Byzantine army in such unprecedented detail will enable us to bring new types of evidence to a debate that has up until now focused largely on historical sources.

68 As in Engels, *Alexander the Great and the Logistics of the Macedonian Army;* Roth, *The Logistics of the Roman Army* (n. 4 above); and Haldon, *Warfare, State and Society in the Byzantine World.*

Key issues, such as the ability of the army to cross broken and restricted terrain, the amount of food required to support the army, and the effects of transportation infrastructure and settlement patterns on route planning and provisioning, can all be modeled in detail for the first time. While the results generated by the model will not give us definite answers to these questions, the various scenarios will help us define parameters within which we can reassess historical sources. Such delineations will mark a substantial advance in our ability to integrate documentary, archaeological, and environmental evidence; to ask more detailed questions of the data we possess; and to establish a more solid basis on which to build hypotheses about resources.

Visualizing the movement of the army and its effect on the resources of visited settlements makes it easier to understand a process previously modeled only using top-down, systemic approaches, as it enables the results of the modeling process to be communicated to an audience unused to interpreting agent-based models. The model itself can be expanded beyond its current scope to include the spread of disease by employing epidemiological models. Disease, more than famine, was an ever-present threat to medieval armies on campaign, which could be seriously weakened by it. An agent-based approach to modeling the introduction and spread of disease through an army would help provide parameters within which historians could evaluate existing theories. The benefits of such a process are, of course, reciprocal. Information held within the historical record provides important, well-established detail that ultimately can be used to validate the outputs of each experiment. The outputs in turn can be used to define parameters within which the historical evidence can be framed. Once such definition has been accomplished, a major goal of the project—to implement a cross-disciplinary methodology to study key historical events—will have been achieved.

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